# Developmental Dyslexia and Implicit Learning in Childhood: Evidence using the Artificial Grammar Learning paradigm

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# DECLARATION

I declare that the present work has been composed by me, it is my own work and that it has not been submitted for any other degree or professional qualification.

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# ABSTRACT OF THESIS

This thesis explores implicit learning in children with developmental dyslexia. While specific cognitive abilities such as phonology and memory have been extensively explored in developmental dyslexia more global, fundamental abilities are rarely studied. A literature review is reported, which indicates that there is a gap in the study of more generic abilities highlighting at the same time, the need of investigating developmental dyslexia in the kind of contemporary context that learning literature provides.

Implicit learning seems a suitable paradigm case to explore global abilities in developmental dyslexia since there have been suggestions that learning becomes more implicit in nature after explicit instruction. Based on the proposed relationship between implicit learning and reading, it is argued that impairments in the mechanisms of implicit learning could mediate selective weaknesses in reading performance in developmental dyslexia. The present thesis tests this argument in a series of three studies that are composed of five linked experiments.

Together the three studies reported in the present thesis provide evidence for the implicit learning abilities in children with and without developmental dyslexia. The results suggest that while implicit learning abilities are found intact in typically developing children, children with developmental dyslexia on the other hand, might be facing an implicit learning deficit that could affect their reading performance and inhibit them from reaching their full learning potential.

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# CHAPTER 1

# OVERVIEW OF THESIS

The thesis will argue that implicit learning provides a good paradigm for investigating generalized deficits in children with developmental dyslexia and shows that children with dyslexia are facing an implicit learning deficit, namely an abstract rule learning deficit. This deficit prevents children with developmental dyslexia from abstracting information in highly complex learning settings and has a knock-on effect on their literacy abilities.

Presently, there are a number of different accounts that lay claims to developmental dyslexia and these are discussed with respect to the specificity of their core etiology and with respect to their general explanatory power in Chapter 2. The literature review illustrates two important findings: First, research in developmental dyslexia is uni-causal and uni-directional and is mainly interested in exploring specific explicit learning abilities. More global and fundamental abilities are scarcely studied. Second, although developmental dyslexia is a condition that affects various aspects of learning, it is rarely studied in the context of contemporary learning literature namely, implicit learning (presented in Chapter 3).

This small but important literature that examines implicit learning abilities in developmental dyslexia is reviewed in Chapter 4. The review shows that the majority of studies that have explored implicit learning abilities in developmental dyslexic populations were done on adults and have almost exclusively utilized variations of one implicit learning paradigm; the serial reaction time paradigm. Given that different implicit learning paradigms could allow different insights into implicit learning abilities, the five experiments of the present thesis examine implicit learning performance using the artificial grammar learning (AGL) paradigm (e.g. Reber, 1967, 1976). The thesis explores, for the first time, implicit learning in primary school children with developmental dyslexia using this particular paradigm (see Chapters 5, 6 & 7).

Following the assumption that development could be better understood by studying both typical and atypical populations (Cicchetti, 1984), AGL performance is measured in children with developmental dyslexia and it is contrasted with that of typically developing children. This way, the nature of the thesis becomes twofold: First, the thesis examines fundamental implicit learning abilities in children with developmental dyslexia; the exploration of implicit learning abilities coupled with well-studied explicit deficits may offer the ground for a better understanding of this condition. Second, it provides additional information on implicit learning abilities in typically developing children so that a clearer picture of how these abilities develop across the lifespan can be formed.

Finally, Chapter 8 discusses the implications of the present findings on implicit learning and developmental dyslexia theory, suggesting areas for future research. Most importantly, the thesis argues that implicit learning abilities should be taken into consideration when developing teaching strategies for both typically developing and developmental dyslexic school populations. The concepts of naturalistic and instructional teaching (Graham, 2000) are discussed, as they are of great importance when planning and implementing intervention strategies for children with developmental dyslexia as well as typically developing children. The thesis considers the overall educational and scientific impact of the reported findings and proposes ways to take research into implicit learning forward. Most importantly, the current work puts forward ways of facilitating children (with and without developmental dyslexia) to reach their full learning potential.

# CHAPTER 2

# DEVELOPMENTAL DYSLEXIA: CURRENT CONTROVERSIES

## 2.1 Aims of Chapter

This chapter reviews theoretical issues about developmental dyslexia, illustrating current controversies in the field. It begins with contradictions in the understanding and definition of developmental dyslexia and moves on to re-consider the grand theories of developmental dyslexia and their implications at both a theoretical and an empirical level. Current theories adopt the view that dyslexia is a specific learning difficulty, often resulting from developmental causal processes. As a result, dyslexia research seeks one core causal etiology to explain the wide spectrum of behavioral manifestations of the condition. However, there is a need to move towards a more dynamic and multidimensional view of developmental dyslexia given the wealth of incoming neurocognitive and behavioral data that associate developmental dyslexia with non-linguistic abilities such as implicit learning (Reber, 1967) (to be discussed in the following chapter).

## 2.2 Introduction

Within formal schooling the abilities to read, spell and calculate are emphasized in such a way that successful learning is highly dependent upon mastering these three abilities. However, there are a number of children reported as having problems in fully succeeding in one or more of these areas. The children have difficulties that lower their performance compared to the performance of their peers. This poor academic performance has an impact on the overall school life of the children as well as on their everyday lives.

‘Dyslexia’ is used as an umbrella term to describe the majority of the learning difficulties that involve a person’s ability to read, spell and/or calculate accurately. It is interesting to note that in an audit on dyslexia and specific learning difficulties policy and practice in Scotland (Reid, Deponio & Petch, 2005) the educational authorities seem to have a varied commitment to the term dyslexia, both in extent and in nature. Reid *et al*. (2005) note that there is a general movement towards a more generic consideration of the term dyslexia and of the way it is perceived. It is doubtless, however, that in the case of parents for instance, ‘dyslexia’ is being used in their everyday language as it simplifies the existing problems. It provides a unified comprehensible framework in which they advocate the educational and legal entitlements of their children. In the case of researchers on the other hand, developmental dyslexia provides a continuing theoretical challenge in an exceedingly complex field.

Early attempts to define and classify different forms of dyslexia concentrate in the notion of ‘typical development’; the behavioral characteristics associated with dyslexia constitute either manifestations of an atypical development or they are the result of an incidental disruption of typical function due to damage - injury in the course of an overall typical development. Thus, the terms ‘developmental’ and ‘acquired’ dyslexia (Shallice & McCarthy, 1985; Shallice, Warrington & McCarthy, 1983) were postulated and are extensively used.

These two forms of dyslexia have different origins and profiles. Developmental dyslexia is the form of dyslexia that is unexpectedly present in an early stage disrupting typical development. Developmental dyslexia describes children who have difficulties with their attempts to learn during childhood. Acquired dyslexia on the other hand, is present in typically developing or typically developed individuals after, for example, following brain damage (Baddeley, 1988) or brain disease (Manis, Seidenberg, Doi, McBride-Chang & Petersen, 1995). The focus of the present thesis is developmental dyslexia.

## 2.3 What is developmental dyslexia?

### 2.3.1 Demographics

Developmental dyslexia has a high occurrence that is estimated between 7-17% of the school-aged world population (Shaywitz & Shaywitz, 2001) and around 4% in the UK school population (see also Eden & Moats, 2002 for a higher reported percentage). This condition is more prevalent in boys than girls (ratio 4:1) (Neanon, 2003). However, other research (e.g. Shaywitz, Shaywitz, Fletcher & Escobar, 1990) has indicated that these numbers may not reflect the true incidence rates. The difference in the rates for each gender may reflect school selection biases: boys are more frequently reported by their teachers as having problems compared to girls (Shaywitz & Shaywitz, 2001) possibly due to behavioral differences between the two genders (Neanon, 2003). One should also note that the reported figures are not in any way normative as they are subject to the limitations of the research tools and to the adopted definitions of developmental dyslexia of the studies that report them.

Vogler and colleagues (1985) report 40% of the boys whose father has been diagnosed with developmental dyslexia are at risk of being diagnosed with the same condition. The percentage of boys with a mother having developmental dyslexia increases to 55% whereas the percentage for girls with either parent diagnosed with developmental dyslexia is 17-18%. Studies from the available literature on the heritability of developmental dyslexia (Castles, Datta, Gayan & Olson, 1999; Olson, Forsberg, Wise & Rack, 1994) tend to show that developmental dyslexia is a heritable and often familial condition.

Irrespective of whether developmental dyslexia is gender-related or not, it appears to affect children from various socio-economic and cultural backgrounds. Despite the fact that the majority of data from different languages (e.g. Eden & Moats, 2002; Paulesu, Demonet, Fazio, McCrory, Chanoine, Brunswick *et al*., 2001) supports its cultural universality, other research, to a lesser extent, provides supporting evidence for the view of developmental dyslexia as a cultural-specific condition (e.g. Koyama, Hansen & Stein, 2008; Siok, Perfetti, Jin, & Tan, 2004). Nevertheless, developmental dyslexia occurs across different languages. Although it is more commonly found in orthographic languages such as English or German, it is also diagnosed in logographic languages such as Chinese (e.g. Ho, Chan, Tsang & Lee, 2002) or Japanese (e.g. Uno, Kaneko, Haruhara & Kaga, 2000). Overall, the data tends to show a similar pattern of behavioral and neuroanatomical characteristics of the people who are diagnosed with this condition even if there are existing variations across languages (e.g. in terms of the writing system i.e. alphabetic or logographic and the orthographic-phonological consistency) and in the views each society holds for learning disorders (Eden & Moats, 2002).

To sum up, developmental dyslexia affects a significant number of children (both boys and girls) that come from various cultural and socio-economic backgrounds and who show similar susceptibility to failure in their encounter with print. Children exhibit a similar pattern of difficulties that make their learning and everyday life arduous. The following section discusses the common characteristics of developmental dyslexia that distinguish it from other reading disorders.

### 2.3.2 Characteristics of developmental dyslexia

According to Rice and Brooks (2004) developmental dyslexia does not describe a sole deficit; it is a cluster of different primary and secondary characteristics (Neanon, 2003) varying in severity, frequency and co-occurrence. More often, we come across difficulties with reading and/or spelling words correctly and with reading comprehension. Also, there might be accompanying problems with memory (retrieving or storing information), orientation and balance (dyspraxia), numbers (dyscalculia) and handwriting (dysgraphia). Although developmental dyslexia is understood as a pattern of difficulties that can incorporate characteristics of other specific difficulties (i.e. dyscalculia or dysgraphia), current orientations view these difficulties as dimensional instead of categorical (Snowling, 2005).

The aforementioned primary characteristics are in some cases followed by other secondary characteristics such as depression, anxiety and low self-esteem. Varying in the degree of severity these secondary characteristics may have a knock on effect on peer relationships, school attendance (e.g. school phobia or refusal to attend) and emotional stability (Neanon, 2003). Consequently, there is always the danger of children with developmental dyslexia being described, for example, as lacking concentration or motivation to work.

There is a consensus that reading problems are amongst the most characteristic markers of developmental dyslexia (Frith, 1999) and thus, have been the center of attention for both theory and research. Reading is a complex and dynamic process that requires a number of skills, which facilitate it and result in its full mastery. These skills can be divided into two main categories: pre-reading skills and skills developed by experiencing reading itself. Pre-reading skills involve for example, matching, rhyming, motor and language skills (Reid, 2003). Even from early on in life, typically developing infants have the ability to recognize (Goswami, 2008) and abstract (Marcus, Vijayan, Bandi Rao & Vishton, 1999) the distributional ( i.e. the statistical) properties of sounds. After exposure to print, additional skills contribute to successful reading such as word attack (e.g. letter recognition and segmentation), word recognition (e.g. blending) and the understanding of meaning of the text (Reid, 2003).

It is catholically accepted (e.g. Goswami, 2008; Snowling, 2000) that phonemic awareness (i.e. the ability to understand that letters have a sound in different combinations) and phonological awareness (i.e. the ability to distinguish the separate sounds of a word) are crucial for competent reading. Phonological awareness is considered a prerequisite for successful reading in both phonographic scripts such as English and Greek (e.g. Gathercole, Hitch, Service & Martin, 1997; Muter, Hulme, Snowling & Stevenson, 2004) as well as logographic scripts such as Chinese (e.g. Siok & Fletcher, 2001). However, there are recent suggestions that in logographic scripts visual orthographic skills contribute more to successful reading acquisition (e.g. Koyama *et al*., 2008).

There is also evidence (e.g. Landerl, Wimmer & Frith, 1997) that there is a systematic relationship between reading performance and orthographic consistency. Reading acquisition becomes more arduous in deep orthographies where the letters and their sounds are not highly consistent compared to shallow orthographies where letters and sounds are highly consistent. Likewise, the occurrence of developmental dyslexia in different languages appears to vary depending on the nature of the orthography (Paulesu *et al*., 2001). Reading in deep orthographies such as English seems to be negatively affected more often compared to reading performance in shallow orthographies such as German.

The central task therefore, in learning to read is the establishment of relationships between letters (graphemes) of printed words (orthography) and speech sounds (phonemes) of spoken words (phonology) for the successful phonological decoding of the text (Vellutino *et al*., 2004). This, in turn, is a prerequisite for accessing its meaning. In other words, there are two basic processes in reading: transforming letters into words and understanding their meaning (Ehri, 2002). A classic view (see Stroop, 1935) is that reading is automatic: the reader is bound to access the semantic meaning of the word when there is sufficient stimulus quality and irrespective of the intention to read or not (i.e. the indirect route of reading) (Caplan, 1992). However, this widely held classic view of reading has been challenged in a series of studies (e.g. Besner, 2001; Melara & Algom, 2003; Stolz & Besner, 1999). The studies provide evidence in favor of a direct route of reading according to which orthography activates phonology directly and in turn, it gradually gives room to whole-word recognition resulting in faster reading (Caplan, 1992).

The proposal that reading is acquired via a phonological route or an orthographic route (e.g. Coltheart, Curtis, Atkins, & Halter, 1993) as described in dual-route models has influenced a long-standing research tradition (e.g. Frith, 1985; Snowling, 1981; Castles & Coltheart, 1993) on subtypes in developmental dyslexia. The search for subtypes of acquired dyslexia examines the cognitive mechanisms for reading following the assumption that a deficit in different routes results to distinct types of dyslexia profiles: the phonological type; and the surface type (see also section 4.1, the double deficit hypothesis).

The majority of studies attempted to demonstrate the existence of similar sub-typing patterns/taxonomies (e.g. surface or phonological dyslexia) in developmental dyslexia as well but with contradictory findings. Case studies (e.g., Campbell & Butterworth, 1985; Temple & Marshall, 1983) proved much of the data on the phonological type and part of data on the surface type (Coltheart, Masterson, Byng, Prior & Riddoch, 1983). Issues such as deviance or delay from typical development (e.g., Bryant & Impey, 1986), reliability and incidence rates are at heart of the proposed taxonomies. In the light of such findings, there are theorists who are comfortable with the notion of sub-typing (e.g. Nicolson & Fawcett, 1990; Stanovich, Siegel & Gottardo, 1997). Subtypes explain individual behavioural differences and are linked with different underlying causal explanations for the distinct deficit profiles. For those theorists who dispute the existence of distinct subtypes on the other hand, individual differences are mainly viewed as dimensional expressions of the same condition (Snowling, 2000). Subtypes are identified with individual differences within dyslexics' reading abilities rather than with distinctive types of abnormal reading performance (Manis, Seidenberg, Doi, McBride-Chang & Petersen, 1996).

To summarize, a wide range of difficulties characterizes developmental dyslexia, the most common and prevalent being reading difficulties. Problematic reading is a recurrent feature in almost all definitions of developmental dyslexia and has influenced the diagnostic procedures. In the following section, this thesis examines definitions of developmental dyslexia from several points of view such as cognitive models, educational policy and intervention, discussing the knock-on effect they have on diagnostic/assessment procedures.

### 2.3.3 Defining and diagnosing developmental dyslexia

Although historically definitions had the tendency to impose labels rather than inform, they are still useful starting points (Reid, 2003) and guidelines for both educators and other professionals. The different traditions create different definitions and in turn, affect how research is conducted and how the data is understood. The definitions that have been employed reflect the different approaches and the underlying course of thinking about developmental dyslexia varying in the degree of addressing issues relevant to diagnosis and intervention; but most importantly to early identification.

We encounter descriptive, working, causal, discrepancy-based and criteria-led definitions. British Dyslexia Association (BDA) states "dyslexia is a combination of abilities and difficulties that affect the learning process in one or more of reading, spelling, writing. Accompanying weakness may be identified in areas of speed of processing, short-term memory, sequencing, auditory and/or visual perception, spoken language and motor skills. It is particularly related to mastering and using written language, which may include alphabetic, numeric and musical notation" (Peer, 2001 cited in Read, 2003, p.2).

Descriptive definitions (such as the aforementioned) point out observable behaviors in the sense of typical characteristics that relate to the learning context along with measurable properties for defining the condition described. Despite the fact that these definitions are free from constraints (Reid, 2003) and facilitate identification (in educational and curricular terms) they do not take into consideration the dual nature of developmental dyslexia at behavioral and cognitive levels. There is not a differentiating approach for behavioral and cognitive deficits as to the way they can be dealt in the classroom.

The difference between behavioral and cognitive factors is more stressed in causal definitions of developmental dyslexia. International Dyslexia Association (IDA) defines dyslexia as neurologically- based and often familial condition, which interferes with the acquisition of language. Causal definitions use inclusive principals (e.g. *is* or *manifested by*) or exclusionary principals (e.g. *is not*) in order to define developmental dyslexia but leave open the part of social policy, as they do not provide guidelines on intervention.

Reid Lyon (1995) claims that to clarify the concept of dyslexia we need to start with a working definition that separates description from causal explanations. On this basis the British Psychological Society (BPS) reports that "dyslexia is evident when accurate and fluent word reading and/or spelling develops very incompletely or with great difficulty" (BPS, 1999a, p.18). Working definitions such as the one proposed by BPS can clarify to an extent decision making at a social policy level but do not resolve interventional issues such as the timing. Although the existence of a phonological deficit is stressed out and phonological orientated teaching strategies can be recruited, the appropriate intervention point is not evident.

Research-based definitions on the other hand, have an advantage of being flexible: they agree with the current research data, especially in the fast developing field of neurological investigation of developmental dyslexia (Lyon, Shaywitz & Shaywitz, 2003). It should be acknowledged that research-based definitions usually accommodate different theoretical viewpoints and provide a link to intervention (Fletcher, Shaywitz, Shankweiler, Katz, Liberman, Stuebing *et al*., 1994; Stuebing, Fletcher, LeDoux, Lyon, Shaywitz & Shaywitz, 2002). They give guidelines for identifying both children who are at risk for developmental dyslexia and children who show negative response to interventional approaches or they are in the need of an alternative remediation. Finally, research-based definitions use inclusion principles specifying the phonological signs, which define who has and who has not developmental dyslexia. However, these definitions overstress the view that developmental dyslexia is a phonological disorder. A single explanation seems rather oversimplifying if we consider the accumulative data, which report deficits in other cognitive (see section 4.2) and non-linguistic abilities (e.g. Nicolson & Fawcett, 1990) in developmental dyslexia.

Discrepancy-based definitions have gained ground and are frequently used (e.g. Ashton, 1997; 2001). IQ is probably the most studied component of definitions of developmental dyslexia and learning disabilities in general. However, it has initiated an endless dispute (Fletcher *et al*., 1994) and has received much criticism (e.g. Stanovich 1996, 1998; Siegal, 1992). The core of discrepancy-based definitions is the unexpected divergence between the mental abilities of the individual and the achieved scores on a range of behavioral tests (e.g. phonological tests, auditory tests such as naming speed, memory tests). This initiated a discussion about whether people with developmental dyslexia differ from low performance populations. IQ discrepancy should not be used as the only definition of developmental dyslexia as it has several limitations, for example the use of often overlapping defining criteria for other learning disabilities or difficulties (Fletcher *et al*., 1994; Stuebing *et al*., 2002). Furthermore, the possibility that a good reader might become even better in time and a poor reader gradually poorer, reveals another weak point of discrepancy definitions; there is a high risk of blurring the boundaries of distinction between aptitude and achievement (Stanovich, 1991).

Fletcher and collaborators (1994) on the other hand, argue that the absence of IQ discrepancy in the definition of developmental dyslexia would cause an immediate turn towards cognitive factors related to the multiple problems that individuals with developmental dyslexia face and would end up to a more effective and less expensive evaluation. However, such absence would make the boundaries between 'garden variety poor readers' (i.e. poor readers due to due to low IQ and readers with developmental dyslexia) less clear (Stanovich, 1988). This would then have implications for identification, intervention and educational provision at practical and policy levels. Nevertheless, intelligence is a very confusing and problematic concept as there is no solid evidence of a systematic relationship between intelligence level and reading performance.

Alternatively, Reid (2002, 2003) emphasizes the importance of early identification, the ongoing monitoring along with professional consultancy and the provision of successful guidelines for assessment and intervention. He stresses the need to take into account individual, classroom and diversity parameters, which in turn will facilitate the development of good early screening tests. As the prevalence of people diagnosed with developmental dyslexia varies according to the definition used (Ellis, 1993); definitions that have a stronger educational or behavioral core will classify different people than definitions that have a bio-medical emphasis (Miles &

Miles, 1999). This has direct implications for diagnosis and indicates that dyslexia cannot be assessed on the basis of a single test and a single cure (Neanon, 2003).

It follows that the list of factors that should be taken into consideration is long when diagnosing developmental dyslexia, ranging from weaknesses and strengths in different types of learning to attainment level, cognitive profile, family history and schooling (Reid, 2003). These factors will not diagnose developmental dyslexia *per se* but will help to create a more dynamic and inclusive profile. This way, ongoing assessment could always be taking place so that the specific educational needs of the children are met in full.

There is a broad range of assessment criteria and tools for diagnosing developmental dyslexia. The number of diagnostic tools used depends on the nature of the definition of developmental dyslexia that is adopted (as stressed above). For example, when the behavioral manifestations of developmental dyslexia are the center of attention then reading and spelling tests (e.g. the Wechsler Objective Reading Dimensions (WORD)) are employed. The reading or spelling ages are calculated and the discrepancy between the expected level of performance according to chronological age and the actual level of performance of the child under test is taken as an indicator of developmental dyslexia.

However, reading and spelling tests are not usually administered on their own. The prevailing view that developmental dyslexia can be more safely diagnosed when the majority of intellectual abilities are within the normal range (as calculated across the general population) brought the need of standardized psychometric measures for those abilities. An example of an IQ scale that is widely used is the Wechsler Intelligence Scale (WISC); it includes a number of sub-tests that assess verbal and non-verbal performance. Siegal (1992) argues that IQ scales do not measure global intelligence but rather other skills related to reading such as short-term memory. So, the administration of global IQ measures does not reflect a comprehensive screening of all the abilities children with developmental dyslexia have (Miles, 1996); IQ measures are rather indicators of specific abilities (see method's section of Chapters 6 & 7).

The use of IQ tests as part of the discrepancy diagnosis of developmental dyslexia has its root in the proposed relationship between intelligence and reading (i.e. poor intellectual abilities compromise reading abilities). However, this relationship is not widely accepted and has therefore been criticized (e.g. Siegal, 1989; Stanovich, 1991). Instead, as mentioned in the previous section, the relationship between reading and phonology has received extensive support (e.g. Stanovich, 1991; Frith, 1995; Hatcher & Snowling, 2002) and as a result phonological assessment has become a corner stone in the diagnosis of developmental dyslexia. The Phonological Assessment Test (PAT) (Muter, Hulme & Snowling, 1997) and the Phonological Assessment Battery (PhaB) (Frederickson, Frith & Reason, 1997) are examples of phonological assessment tools in the diagnosis of developmental dyslexia.

There are also screening batteries that aim to assess whether a child's the difficulties emerge from other 'problematic' sources (e.g. grounded in biological substrates).

There are test batteries (e.g. rapid naming or digit span) developed on the basis of new findings about cerebellar involvement or the naming speed, in developmental dyslexia (see section 4); the Dyslexia Screening Test (DST) (Nicholson & Fawcett, 1996) is a good example.

Indisputably, the list of tests and batteries that are used both as screening and as diagnostic tools is long whilst the choice of tools depends on the aim of the assessment or the design of the research study (see Chapters 5, 6 & 7). However, the diagnosis of developmental dyslexia is much more than the administration of tests (Reid, 2003). It should be an ongoing assessment of all levels of interest (i.e. educational, behavioral and psychological) so that the implications of developmental dyslexia for the children themselves, their families, their schooling and their everyday life are brought to the surface and are dealt successfully. This kind of assessment can in turn, provide guidelines for fruitful intervention strategies that will ameliorate the dyslexic characteristics.

### 2.3.4 Summary and discussion

It is clear that a solitary and unanimous explanation and definition of developmental dyslexia is difficult to construct; there are arbitrary pre-existing factors responsible for ‘typical’ development (elaborating on them is beyond the scope of this thesis), which could result in a broad range of characteristics associated with developmental dyslexia. A bare explanation in behavioural terms can be misleading, as compensating strategies may camouflage potential underlying cognitive deficits making it difficult to acquire a clear picture (Frith, 1999).

A definition of developmental dyslexia should also be coordinated with current trends in brain and biology research that test the role of brain areas such as the cerebellum (Nicolson & Fawcett, 2003) and biological factors such as the role of sex (e.g. Castles *et al*., 2002). Frith (1999) proposes to take into account the employment of compensating strategies that can potentially balance out the severity of the neurobiological manifestations given that the human brain has alternative ways to ameliorate dysfunctions and protect its system. In the context of this thesis however, as well as for theoretical and methodological purposes, developmental dyslexia is understood as neurobiological in origin and as a condition that is usually evident when reading and writing develops with difficulty (BDA, 1999) despite normal intelligence, no sensory or neurological impairment and adequate educational and socio-economic opportunities (DSM IV, 1994).

It needs to be said that there is a dialectic relationship between definition and theory in the sense that a definition may (or should) encapsulate the current theories and that the theories provide an empirical path for a definition to be formulated. The sphere of characteristics that are considered symptoms is very broad while there is still an ongoing dispute over the nature of other characteristics associated with developmental dyslexia (extended discussion takes place in the next section). At the same time, the notion of a core difficulty (with other difficulties being the result of the prevailing one) (Snowling, 2000) and the notion of multiple difficulties that can be categorized as subtypes of dyslexia (termed as ‘dyslexias’) lies at heart of scientific thinking influencing the way research in developmental dyslexia is conducted.

In the following section, the thesis will review the various causes of developmental dyslexia in all levels of description: biological, cognitive, and social. Initially, biological accounts will be discussed followed by considerations of cognitive and social accounts of developmental dyslexia. The review illustrates that research in developmental dyslexia focuses mainly on the search of a core causal explanation. But the plethora of explanations that are put forward is indicative of the lack of a core cause while their limited explanatory power points towards the need for a different framework in which to theorize developmental dyslexia. This different framework can be summarized in the proposal that developmental dyslexia "…needn't satisfy each and every property encoded in the concept's structure as long as it satisfies a sufficient number of them" (Laurence & Margolis, 1999, p.7).

### 2.4 Causes of developmental dyslexia

Developmental dyslexia is usually studied in uni-directional (i.e. following the assumption of the close relationship between brain functions and their behavioral outcomes) and uni-causal (i.e. searching for one cause that can lead to the observed symptoms) ways. The study of the brain (both as an organ with different regions and as function) in individuals diagnosed with developmental dyslexia accepts implicitly the notion of modularity. According to Flombaum, Santos and Hauser (2002) "modularity is the thesis that the mind contains independent input systems that, when engaged, are restricted in the types of information that they can consult" (p. 107). In other words, a very important criterion for modularity is that there are parts of the mind that are inaccessible to other parts of the mind or to the information the other parts hold (Bryson, 2004).

This inaccessibility leads to another criterion for modularity that is linked with the cognitive processes: Since cognitive processes depend on representations then different processes with different representational structures (and their resulting knowledge) cannot access the content of one another (Bryson, 2004). This criterion is of great importance in the study of developmental dyslexia and in the better understanding of some of the dyslexic phenomena; such as dissociations between double/multiple deficits or selective deficits.

The notion of modularity has various interpretations (Mitchell, 2006) yet, developmental dyslexia theory adopts modularity in its extreme view. Modularity in developmental dyslexia research almost implies a direct and causal relationship between brain functions and the observed behaviour (Pennington, 2006). Most theories support directly or indirectly a linear relationship between brain abnormalities, their corresponding underlying cognitive deficit and in turn, their behavioural outcomes. This assumption explains not only the uni-directional nature of the neuropsychological models that have been applied in the understanding of dyslexia but also the seeking of 'pure' cases, characterised by one core deficit (i.e. uni-causality).

### 2.4.1 Biological explanations

There has been an increase of interest in examining the heritability of learning disorders (Fletcher, Francis, Shaywitz, Lyon, Foorman, Stuebing *et al*., 1998; Siegal, 1992; Stanovich, 1991; Rutter, 1989) and the extent to which biological and cognitive factors[1] influence reading ability in particular. The biological basis of developmental dyslexia is extensively explored, as other aspects of development appear to be normal. The bulk of data supporting a biological basis of developmental dyslexia comes from genetic, autopsy and brain studies.

To begin with, the prevalence of developmental dyslexia in boys provides support to the argument of genetic heritability. Different genetic theories argue in favor of one or more than one specific genes (e.g. Grigorenko, Wood, Meyer, Hart, Speed, Shuster & Pauls, 1997; Pennington, 1999) being responsible for the occurrence of the condition. We come across single-gene theories such as the Autosomal dominant transmission (when one parent can transmit the gene) and the X-linked recessive transmission (when either parents can transmit the gene but the child will be only affected if he/she hasn't got a normal copy of it) as well as multi-gene theories (Pennington, 1999; Plomin DeFries, McClearn & McGuffy, 2001). Chromosome 6 (Fisher, Marlow, Lamb, Maestrini, Williams *et al*., 1999a) and Chromosome 15 (e.g. Smith, Kimberling, Pennington & Lubs, 1983) are considered possible gene loci associated with developmental dyslexia.

However, there are children with developmental dyslexia who have neither of their parents diagnosed with the condition (Plomin *et al*., 2001). Thus, familial disposition does not necessarily imply genetic heritability since there are other factors that can be familial or powerful predictors of good reading performance but

[1] There are neuroimaging studies exploring e.g. brain activity (Shaywitz *et al*., 2003; Paulesu *et al*., 2001; Simos, Breier, Fletcher, Bergman & Papanicolaou, 2000) or brain functional imaging (Corina et *al*., 2001; Brunswick *et al*., 1999; Rumsey *et al*., 1997) during reading to reveal the neural and functional substrates of reading in typical and reading disabled populations.

do not have genetic basis (e.g. Elley, 1994). Genetic theories receive further criticism, as they suggest more than one gene to be responsible for developmental dyslexia while they haven't firmly established how these genes affect reading development or how they interact with the environment.

Post-mortem studies on the other hand, on the brains of people with developmental dyslexia provide more firm evidence for differences and/ or anomalies in their brain structure compared to typically developing brains. Autopsy studies have shown anomalies in the magnocellular neural system, for example, and in the symmetry of the two brain hemispheres (e.g. Galaburda, Sherman, Rosen, Aboitiz & Geschwind, 1985; Livingstone, Rosen, Drislane & Galaburda, 1991). The autopsy data initiated *in vivo* studies that aimed to discover whether there are differences in brain structure and function of people with developmental dyslexia during task performances. The neuroimaging studies revealed abnormalities in the temporal lobes (Hynd, Shemrud-Clikeman, Lorys, Novey & Epiopulos, 1990; Larsen, Hien, Lundberg & Odegaard, 1990), in the cerebellum (Rae, Harasty, Dzendrowsky, Talcott, Simpson, Blamire *et al*., 2002) and in the connectivity between the two hemispheres (e.g. von Plessen, Lundervold, Duta, Heiervang, Klauschen, Smievoll *et al*., 2002).

Based on the aforementioned neuroimaging data that link developmental dyslexia with anomalies in magnocellular system, psychological studies aim to explore visual and auditory processing. Studies from the available literature suggest that individuals with dyslexia have difficulties with several visual (Lovegrove, Bowling, Badcock & Blackwood, 1980; Livingston *et al*., 1991; Stein & Walsh, 1997) and auditory tasks (McAnally & Stein, 1996; Tallal, 1980; Tallal, Miller & Fitch, 1993). In the light of such findings, the unifying magnocellular theory (Stein & Walsh, 1997; Stein, 2001) is put forward to explain those difficulties. This theory holds that impairment in the cross-modal brain systems (the parvocellular and magnocellular systems) that process rapid streams of stimuli results in the reading impairments found in developmental dyslexia. The magnocellular theory encompasses the visual and auditory deficits that were traditionally studied separately accounting for a varied pattern of symptoms. Those symptoms range from unstable saccadic eye movements (e.g. Prado, Dudois & Valdois, 2007) and unfading visual images (Vellutino, Fletcher, Snowling & Scanlon, 2004) to problems with short and rapidly presented auditory stimuli (Tall, 1980).

The severest criticism the magnocellular theory receives stems from an inability to replicate consistent findings to support the postulated auditory and visual disorders in populations with developmental dyslexia (Ramus, 2004; Ramus, Rosen, Dakin, Day, Castellote, White & Frith, 2003). In response to this inconsistency of the findings, there was an increase in the study of attentional processes. Attention is critical for all the tasks (Moores, 2004) in terms of shifting visual attention by the presence of cues in the visual field (Facoetti, Paganoni, Turatto, Marzola, & Mascetti, 2000) and the ability to control the size of attentional focus (e.g. Benso, Turatto, Mascetti & Umilta, 1998). Reading requires (amongst other cognitive processes) a precise and accurate visual analysis of the written words that is accomplished by triggering the focal attentional mechanism. It has been proposed that poor readers rely mostly on holistic information based on a more distributed attentional modality (Williams & Bologna, 1985). The studies show that participants with developmental dyslexia cannot shift their attention in response to peripheral cues as well as controls. They also have difficulty maintaining their attention focused on a target for longer periods of time so that the target is presumably processed less adequately (Pothos & Kirk, 2004).

In parallel, Nicolson and Fawcett (1999, 1996, 1994, 1990) and their colleagues (Fawcett, Nicolson & Dean, 1996; Nicolson, Fawcett, Berry, Jenkins, Dean & Brooks, 1999; Nicolson, Fawcett & Dean, 1995, 2001) propose another neurobiological perspective of developmental dyslexia based on cerebellar activity, which has been extensively associated with automatization of new skills (Nicolson & Fawcett, 1990). They study motor performance in developmental dyslexia (using also PET) presenting data of low activation in the cerebellar activity drawing support from brain imaging studies (e.g. Rae *et al*., 2002). This low activation of the cerebellum results in motor and automatization difficulties, the former causing poor articulation and in turn phonological impairments and the latter failure in fluent word recognition. Both the motor deficit and the failure to execute actions in such a way that they become automatic, result in problematic reading. Nicolson and Fawcett (1990) acknowledge that there are occasions where individuals with developmental dyslexia in spite of this cerebellar abnormality and its resulting difficulties can demonstrate normal performance as a result of compensating strategies. In other words, Nicolson and Fawcett (1994) propose that dyslexics have a deficit in acquiring automaticity for new skills that is masked with hard work (Reid, 2003).

In Nicolson and Fawcett's (2001) model there is a direct link between cerebellar functions, articulatory skills, phonology and reading. The model illustrates a strong relationship between the motor components of speech and the acquisition of phonological skills. However, the detrimental effect of the motor components of speech on phonology has been questioned by data coming in from the study of dysarthria and apraxia where they are recorded cases of individuals exhibiting intact phonological abilities (Ramus *et al.*, 2003). Recently, Nicolson and Fawcett (2007) proposed a specific procedural learning deficit: dyslexic phenomena arise not only from abnormalities in the cerebellum but also from the connections of the neural systems linked to the cerebellum (Laycock, Wilkinson, Wallis, Darwent, Wonders, Fawcett *et al*., 2008). Problems in the connectivity of neural circuits associated with the cerebellum may cause problems, for example, in information processing and integration of information resulting in problems in skill acquisition (Laycock *et al*., 2008). However, due to the extremely limited number of anatomical data on the cerebellum in dyslexic populations (Finch, Nicolson & Fawcett, 2002) no solid conclusions are made.

Despite the criticism (Ramus *et al*., 2003) that the model has received (due to the links it makes between articulation and good reading abilities) both the cerebellar deficit hypothesis and the more generic automatization deficit have been extensively used as explanatory frameworks in a number of studies associating developmental dyslexia with deficits in other areas of contemporary interest. Nicolson and Fawcett's work shifted the focus of theorizing about developmental dyslexia towards the possibility of more generic existing deficits that altered the way developmental dyslexia is conceptualized placing it in a broader-global spectrum. Most importantly, their seminal work viewed developmental dyslexia, for the first time, in the context of skill learning, associating reading difficulties with fundamental learning skills. As stated earlier, developmental dyslexia has been almost identified with reading disability and thus a growing body of research aims at exploring the underpinnings of the reading problems diagnosed in dyslexic populations. This stream of research has its root in the prevailing view that learning an alphabetic writing system requires the brain to map letters (graphemes) to mental representations of the corresponding basic speech sounds (phonemes) (see section 2.3.2).

### 2.4.2 Cognitive explanations

Currently, developmental dyslexia research is serving two main purposes. The first purpose is to give explanations for the two core behavioral markers, in particular reading and spelling problems; developmental dyslexia is characterized as a written language disorder (Snowling, 2000). The second purpose is to demonstrate the causal or explanatory links between the aforementioned behaviors and their possible underlying anatomical and cognitive mechanisms.

With early good phonological awareness being a strong predictor of later fluent reading (Snowling, 1998; Gathercole & Baddeley, 1993) research on the phonological abilities of people with developmental dyslexia produced extensive supporting data for a phonological deficit (e.g. Gathercole & Baddeley, 1993; Snowling, 1998, 2000; Stanovich, 1986; Stanovich & Siegal, 1994; Vellutino *et al.*, 2004; Ramus *et al.*, 2003). Fluent readers have fully developed phonological abilities and use visual decoding strategies only as means to facilitate their phonological decoding that is primarily induced when they are encountered with print (Shankweiler, Liberman, Mark, Fowler, & Fischer, 1979). It follows that a phonological deficit prevents successful reading from being accomplished (see section 2.4 above) as the decoding of new words becomes difficult due to the use of visual decoding strategies instead of phonological strategies (Snowling, 1998).

The failure that readers with developmental dyslexia show in non-word reading (Gathercole, Willis, Emslie & Baddeley, 1994; Rack, Snowling & Olson, 1992), segmentation and other phonological tasks have been widely accepted (Fawcett & Nicholson, 1994) as markers of problematic phonological ability and as indicators of a core phonological deficit (Snowling, 2000). These indicators have been extensively used to explain reading disability and initiated research into other abilities that are directly or indirectly related to phonology and which, in turn, could affect reading performance. This large body of research associates failure in mastering good phonological awareness with deficits in verbal short-term memory (e.g. Gathercole & Baddeley, 1993; Rack, 1985; Tijms, 2004), repetition (Snowling, 1981; Snowling, Goulandris, Bowlby & Howell, 1986) and naming speed (e.g. Snowling, 2000; Snowling, van Wagtendonk & Stafford, 1988).

Baddeley (1983, 2000) proposed a model of working memory with three systems; a central executive with two ‘slave’ components, the phonological loop and the visuospatial sketchpad. His working memory model is supported by brain imaging studies that locate the proposed separate components (Carter, 1998; Brunswick, McCroy, Price, Frith & Frith, 1999). Poor non-word reading performance supports the possibility of a working memory deficit as the ability to read non-words lies upon the activation of the phonological loop (Gathercole *et al*., 1994) and involves accurate speech perception and distinct phonological representations (Holopainen, Ahonen & Lyytinen, 2001). Pickering (2000) provides an account of the problems people with developmental dyslexia. This includes problems in phonological repetition, in retaining of phonological information (with rehearsal or repetition), in using phonological memory strategies and problems with verbal labeling of pictures and lists.

Although the phonological processing deficit accounts for most of the dyslexic symptoms, it has received criticism. Castles and Coltheart (2004) argue against the notion that the correlation between impaired phonological awareness and poor phonological representations is viewed (or implied) as a causal relationship that explains developmental dyslexia. They argue that such causal relationship has not been established and so, poor phonological awareness could be the result of reading disability. It is often the case that the phonological deficit does not explain a spectrum of features of developmental dyslexia such as visual, motor and fluency problems.

Interestingly, the finding that phonological problems are not always accompanied by problems in naming speed (i.e. the ability to quickly recognize and retrieve linguistic information that is visually presented) and *vice versa*, has raised the issue of whether phonological ability and naming speed were two separate sources affecting fluent reading (Wolf & Bowers, 1999). Based on research evidence suggesting there are subgroups of children exhibiting problems in either or both domains (Compton, DeFries & Olson, 2001; Ho, Chan, Tsang & Lee, 2002), Wolf and Bowers (1999) propose the double deficit hypothesis to explain this pattern of problems. They argue that naming speed (fluent reading) and phonological awareness (accurate reading) contribute differentially to good reading performance. Therefore, deficits in these areas should be considered separately when creating links between the behavioral signs of developmental dyslexia and its cognitive underpinnings.

Although, the double deficit hypothesis has received support from research data (Compton *et al.*, 2001; Frith, Landerl & Frith, 1995; Wimmer, Mayringer & Landerl, 2000) it has also received criticism (Davis, Gayan, Knopic, Smith, Cardon, Pennington, Olso & Defries, 2001; Meyer, Wood, Hart & Felton, 1998). The relationship between fluency and phonological processing is not extensively explored so, one cannot safely suggest that these processes are separate from one another (Meyer *et al.*, 1998).

### 2.4.3 Models of multiple explanations

#### 2.4.3.1 The Morton- Frith model

Moving away from a deterministic model that places emphasis on one central deficit explaining all behavioral outcomes will facilitate diagnosis, intervention and early identification of developmental dyslexia. Frith (1995, 1999) and earlier Morton and Frith (1993, 1995) propose a multi-factorial framework in which different levels can include hypothetical and probabilistic etiologies anchored with findings from their corresponding case studies. The framework itself takes into account four areas of interaction (i.e. environment, behavior, cognition and biology). These areas include various environmental, biological, cognitive and behavioral factors; all having a potential explanatory power over specific outcomes in each of these areas.

Although the Frith model is not a new framework, however, it seems to resolve some of the paradoxes (Frith, 1999) that have troubled specialists working in the field of developmental dyslexia as it brings together all conflict stances under a common frame of mind that ameliorates such existing controversies. Although, Frith (1999) refers to a 'dyslexia syndrome', the framework can be viewed in a much broader way to allow the formation of testable multi-level predictions and to reconcile rival theoretical standpoints. This framework brings together contradicting hypotheses for developmental dyslexia and creates the space for new research domains associated with dyslexia such as implicit learning (Chapter 3).

What seems to be the most interesting about this model is that the biological, cognitive and behavioral levels interact with environmental factors and can have an impact on the kind of dyslexic characteristics that are present (Reid, 2003). These environmental (and social) factors can affect individuals with developmental dyslexia in different ways depending on the context and may have a knock-on effect on the learning experience and the learning outcome. These factors are briefly discussed in the following section.

### 2.4.4 Social and environmental explanations

Apart from the hypotheses outlined above that link behavior with the mind and the mind with the brain, there are social and environmental explanations of developmental dyslexia. Although such factors have not gained ground because of their inability to satisfactorily explain developmental dyslexia, they can still affect the way individuals with developmental dyslexia experience difficulties (Spear-Swerling & Sternberg, 1998).

The public perception concerning literacy problems seems to be influenced by the educational and social history, imposing labels in an attempt to simplify complex concepts: since formal (taught) learning became prominent it placed an emphasis on conscious successful learning highlighting the abilities to read, write and calculate. Focusing on this type of learning would necessarily imply that failure to acquire the aforementioned skills constitutes a problem. Currently, children are measured against nationally fixed standards and are ‘obliged’ to meet targets: failure to meet those standards results to children being diagnosed with learning problems (Poole, 2003). Most importantly, it is very difficult within this framework of thinking to (a) recognize children who are at risk of reading failure before they actually fail; children must fail in school before they are identified (Poole, 2003) and; (b) incorporate the view that children with developmental dyslexia may be ‘different’ rather than ‘damaged’; and ‘gifted’ in some areas rather than ‘failing’ in some others (West, 1997; Davis, 1997).

Historically, the notion of learning difficulties (and developmental dyslexia) shares links with philosophical and psychological trends. There was a turn away from a behaviorist stance of learning (i.e. mainly exploring the environment) to an individualist mental processing approach of learning (i.e. an act or process of knowing, Gestalt psychology). The prevailing 'cognitive orientation of learning' (Smith, 1999) set the standards when thinking about learning. "Instead of acquiring habits, learners acquire plans and strategies, and prior knowledge is important" (Hartley, 1998 p.18). Leaning is associated with expectations, inferential and connectionist strategies. This, in turn, brought at heart of the discussion the notion of intelligence and the speed of information processing of the individual. Subsequently, any delay in this process is thought of as lack of intelligence; intelligence is equated with quick thinking so, people who seem to be slower are perceived as unintelligent.

The most challenging question the aforementioned explanations pose is whether developmental dyslexia, amongst other learning difficulties, is a historical and/or cultural manufacture of the 'post-reading' society or whether it pre-exists as symptomatic marker of biological and/or cognitive abnormalities that can be described as syndrome onset in the lifespan. Snow (1991) found that children who grow up in a home environment that places weight on 'literacy' are more likely to progress in reading than children of similar age who grow up in contexts that do not provide many 'literacy stimuli'. According to Hallam (2002) adequate auditory high-pitched stimulation facilitates body coordination and given that parents and especially mothers adopt high-pitched speech communication with infants, it is likely that the lack of such stimulation early in life may increase difficulties in coordination later in life. Hart and Risley (1995), using cross socio-economic samples to measure speech style and complexity patterns between mothers and their babies, found high correlations between those measures and child's later language skills, vocabulary skills and IQ tests for vocal and spoken language (Poole, 2003).

In the above examples, different social and environmental factors are taken into consideration to explain developmental dyslexic phenomena. The data strongly suggests that there are biological, cognitive and behavioral markers for developmental dyslexia. Yet, the numerous social and environmental influences on developmental dyslexia should also be acknowledged to form a more complete picture of the condition and the variance of its characteristics in the population. Although an environmental paradigm for developmental dyslexia (Poole, 2003) seems advantageous, the scientific paradigm that is currently employed for the exploration of developmental dyslexia can still produce important evidence for specific aspects of this condition.

### 2.5 Summary and discussion

The major theoretical tension between social/environmental explanations of developmental dyslexia and cognitive/biological theories is whether developmental dyslexia is the same as any other reading difficulty. This tension is created because most of the cognitive and biological accounts try to define development dyslexia using uni-directional and uni-causal explanations. However, a unitary causal theory should have discriminant validity: it should provide the theoretical and practical framework to discriminate developmental dyslexia from other learning difficulties in which deficient reading is a cardinal marker and explain at the same time other co-existing deficits. Following general symptomatology as the only means to describe and explain developmental dyslexia does not seem to satisfactorily address the clinical and sub-clinical manifestations of dyslexic profiles; the diversity of dyslexic profiles call for a different approach.

At the same time, one cannot override the need for establishing universals (e.g. genetic and familial predisposition) for learning difficulties and developmental dyslexia in specific. This establishment could initiate new research streams in multi-cultural and cross-national/linguistic contexts towards the exploration and revelation of other possible mediating or moderating factors. It might be the case that in the attempt to discover universal characteristics other factors might emerge as strong predictors of developmental dyslexia differing from the ones that have been heavily studied and traditionally associated with it (see Chapter 3).

Moores (2004) stresses the importance of the methodological approaches that one takes each time in conveying true deficits and proposes ways to solve some of the problems. For example, she proposes to compare brain activity in tasks that both typically developing participants and those with developmental dyslexia perform well or to modify commonly used paradigms in such a way to allow strong dissociations to emerge. She acknowledges however, that the approaches she proposes suffer in some of their aspects. For example, they cannot help us distinguish between a delay in a process and a difference in it and thus, should not be used in a normative way. Vellutino *et al.* (2004) conclude that only the phonological deficit shares a causal relationship with reading; good phonological abilities predict good reading performance whereas poor phonological abilities predict poor reading performance. However, one should not ignore the long list of other deficits that have been associated with developmental dyslexia and can affect reading in different ways or exclude on the other hand, the possibility of other deficits that cannot be detected or have falsely described (Moores, 2004).

To realize how complex the scenery of dyslexia is, will shift the focus of discussion away from the attempt to construct an approach that will become authoritative (Miles, 1995). Instead, the problematic nature of defining and explaining developmental dyslexia could be resolved if both definition and theory are considered within a multifunctional framework that includes behavioral, cognitive, biological, social and environmental factors (Frith, 1999). The need of a multi-factorial framework in which to understand developmental disorders generally and dyslexia in specific arises from both the luminance of its biological underpinnings and the issue of co-occurrence or causation, which has been tacitly illustrated in the discussions that took place in the previous sections of the current chapter.

The possibility that developmental dyslexia has a neurodevelopmental origin is gaining ground; the data is in support of this case and enhances the inclination towards a consensus regarding its biological and cognitive underpinnings. However, there are still grey areas in the study of developmental dyslexia that need further clarification and give rise to new streams of research. The difficulty single or double deficit models have in explaining the variability in the profile of children with developmental dyslexia highlights the need for an integrated model. This model should allow more generic conceptualizations of developmental dyslexia and thus, encourage research in other domains that have not been traditionally associated with developmental dyslexia. Taken together, the need for a multi-causal framework and the search for indicators of developmental dyslexia (e.g., culture and/or language independent) prior to the onset of reading acquisition can illuminate those grey areas.

If we view developmental dyslexia as a network of features that can overlap with other features associated with different learning difficulties, this can serve two major purposes. First, it may solve the current theoretical contradiction in the field of developmental dyslexia by looking at it through a different prism; a dimensional view of developmental dyslexic phenomena rather than a categorical view of such phenomena. Second, it provides the ground for the study of developmental dyslexia in the contemporary learning literature which incorporates other types of learning such as implicit learning (is discussed in Chapter 3) that can help us gain a better understanding of developmental dyslexia. By implicit learning I refer to the intuitive process (Reber, 1989) that takes place when we acquire information without intending to do so (Cleeremans, 1998) and in the absence of the ability to verbalize the acquired knowledge (Seger, 1994).

Implicit learning is one of the new areas attracting research interest in developmental dyslexia (see Chapter 4) not only because it provides information on more global-general abilities in line with the aforementioned neuro-developmental view of dyslexia but also because of its proposed relationship with reading (Chapter

3, section 9). Reading problems are considered cardinal markers or defining measures of developmental dyslexia hence, it is essential to explore more global abilities that underpin reading performance. Most importantly, focusing on implicit learning can produce an interesting new set of data. It can potentially elucidate more innate and general abilities that could play a major role in the understanding of what is being eventually observed. The thesis will outline, in the following two chapters, why implicit learning became of interest in the study of developmental dyslexia and why it is the focus of the present work. The next chapter will review research on implicit learning in typical and atypical populations.

# CHAPTER 3

# IMPLICIT LEARNING: A REVIEW

### 3.1 Aims of Chapter

The study of developmental dyslexia as outlined in the previous chapter has concentrated on the specific conscious (explicit) experiences of the children diagnosed with this condition. As illustrated, problematic reading (and its underlying processes) has been the main focus of research. The phonological deficit hypothesis (e.g. Snowling, 2000) is postulated to account for the reading problems children with dyslexia face. However, the broad 'symptomatology' of dyslexic reading problems has led research into more fundamental processes (e.g. Nicolson & Fawcett, 1990; Nicolson, Fawcett & Dean, 2001) that are proposed to underlie successful reading, such as implicit learning (Gombert, 2003). Implicit learning is viewed as skill/habit (Squire, Knowlton & Musen, 1993) that engages motor, perceptual and cognitive processes. In the light of such a view, it becomes clear that the study of developmental dyslexia in the context of implicit learning is highly profitable in our search for a more profound understanding of the possible causes for reading failure.

Although the possibility of separate explicit and implicit learning systems is still under scrutiny (e.g. Green & Shanks, 1993), the distinction between explicit and implicit learning is a longstanding tradition. Different learning types are associated with different abilities: generally, explicit learning is closely related to conscious abilities of specific nature (e.g. Schacter, 1992) whereas implicit learning is associated with incidental, automatic and more global abilities. This chapter reviews fundamental theoretical and methodological concepts of implicit learning. Furthermore, it illustrates how implicit learning abilities appear to function in typical development drawing evidence from a wide range of relevant studies in typical and atypical populations; both children and adults. Finally, the chapter highlights the relevance of implicit learning themes to the study of developmental dyslexia leading the way for the comprehensive review on implicit learning and developmental dyslexia studies that takes place in the following chapter.

### 3.2 Can we learn implicitly?

Learning is a crucial and vital human ability in a constantly changing environment; it is viewed as a rather dynamic process of manipulation and transformation of information (Orban, Lungu & Doyon, 2008). During learning, complicated and intense brain activity takes place with neural networks being stimulated in different areas, combinations and degrees. To be able to identify the areas that have immediate connection with different learning experiences, a distinction is made between explicit (or declarative) memory and implicit (or non-declarative/ procedural) memory. This distinction is made not only to accommodate the different learning processes but also to describe their outcomes. Explicit memory is related to conscious awareness of the subject during the learning procedure and to the use of previously encoded experience to explain the current learning experience. Implicit memory on the other hand, is linked to unconscious retrieval of information previously coded; the subject uses stored information to explain a current behavior but in the absence of awareness.

The view that along with fully intentional learning experiences (e.g. Tarpy, 1997; Cleeremans, 1997) there are learning experiences that “occur as unintentional consequence of human experience” (Forkstam & Petersson, 2005, p.435) and which are not available to conscious recollection (Dienes & Berry, 1997), is not new. Reber (1989) argues in favor of the pre-existence of incidental learning in evolutionary terms (supremacy of the unconscious) and consequently, of its fundamental role in establishing cognition (Seger, 1994). It is widely accepted (e.g. Folia, Udden, Forkstam, Ingvar, Hagoort & Petersson, 2008) that people have innate learning mechanisms that allow them to acquire the structural regularities of their environment in a non-conscious manner (Reber, 1993). More recently, according to Goschke and Bolt (2007) the adaptation of our behavior to recurring and sequential patterns is a fundamental function of learning. It follows that this structural regularity in the environment makes the encoding and exploitation of these regularities an adaptive advantage (Conway & Pisoni, 2008).

A bulk of data that supports the distinction between conscious and non-conscious learning comes from neurocognitive studies on amnesic patients (e.g. Cohen & Squire, 1980; Squire, 1992) due to the almost universally accepted relationship between memory and learning (Shanks & St.Johns, 1994). Although amnesic patients have significant impairments in declarative functions (i.e. hippocampal memory system), they are found to be spared in procedural skill learning tasks (e.g.

Cohen & Squire, 1980). There is also evidence of unintentional and automatic learning taking place in a number of behavioral studies that manipulated the degree of available attentional resources (see Goschke, 1997 for a review). The studies provide evidence of learning under conditions where the available attentional resources are diminished (e.g. Jimenez & Mendez, 1999; Shanks & Johnstone, 1999) or conditions where unattended information can still induce learning (e.g. Heurer & Schmidtke, 1996).

To distinguish between the two different types of learning mentioned above, the terms ‘explicit learning’ and ‘implicit learning’ are widely used. Explicit learning is the process by which knowledge is acquired via “deliberate and conscious attempts” (Howard, Howard, Japikse & Eden, 2006, p. 2). In other words, explicit learning is thought to be present when people learn with the use of analytical strategies and hypothesis testing that refer directly to conscious learning processes that can be recalled at any time. Implicit learning on the other hand, “was first used to characterize how one develops intuitive knowledge about the underlying structure of a complex stimulus environment” (Reber, 1989, p.219). Perruchet and Pacteau (1991) describe implicit learning as being unintentional and automatic in the sense that it requires few or no attentional resources and being out of intentional control.

At this point, it has to be stressed that although the terms implicit learning and implicit memory are often used interchangeably, they differ in a number of ways. Presenting in detail the theoretical and methodological differences between the two notions is beyond the scope of the thesis. However, it has to be noted that there are significant differences in the way the two notions are studied. Implicit memory research typically uses subliminal stimuli (see Ghoneim & Block, 1992 for a review) or single word stimuli (e.g. Schacter, 1992). Implicit learning research on the other hand, involves supraliminal, non-verbal stimuli of high complexity in terms of the structural relationship such stimuli share (Cleeremans *et al.*, 1998). Most importantly, implicit memory typically involves the incidental activation of knowledge that already exists while implicit learning refers to the acquisition of new knowledge that is incidentally activated (Altmann, Dienes & Goode, 1995). Thus, the gains from studying these notions separately become evident.

Central feature in the description of the two different types of learning (i.e. explicit and implicit) is the notion of awareness; mostly in the sense of the accessibility (explicit) or inaccessibility (implicit) of the acquired information (Dienes & Berry, 1997). The majority of the researchers in the learning literature (e.g. Dulany, Carlson & Dewey, 1984; Shanks & St.John, 1994) are more comfortable with the notion of awareness mediating learning as this has been extensively supported by lines of research on flanker effects and dichotic listening (Shanks, 2004). But in explicit/conscious learning situations the number of the hypotheses that can be tested simultaneously from our memory systems is bound to be limited (Baddeley, 1983). Cleeremans (1997) proposes that implicit cognition (and in turn, implicit learning) is more advantageous in processing highly complex information. The implicit learning system processes information that contains multiple regularities due to the lack of any memory limitations (explaining this way the data on semi-intentional or unintentional experimental conditions mentioned above).

Evidence from neuroimaging studies (e.g. Berns, Cohen & Mintun, 1997; Hazeltine, Grafton & Ivry, 1997; Schacter, 1992; Squire, 1994; Tulving, 2000) adds weight to the suggestion that we can learn implicitly as well as to the possibility of a separate learning system processing unattended information (e.g. Grafton, Hazeltine, & Ivry, 1995). Taken together, the mounting neuroimaging studies suggest dissociation between the two learning systems and support the possibility different learning systems relying on different neural networks (Thomas, Hunt, Vizueta, Sommer, Durston, Yang & Worden, 2004); there is neural activation in different brain areas depending on whether participants are aware or unaware of their learning material. Although the possibility of two separate learning systems is still under investigation, there is accumulative evidence in favor of the existence two different learning systems that operate in parallel and may interact under specific learning conditions (e.g. Tulving, 2000).

In general, implicit learning plays an important role in numerous aspects of typical and atypical development. It is closely associated with innate structures and preverbal procedures that underlie different areas of development such as language (e.g. Karmiloff-Smith, 1986). It is proposed (Ehri, 1990; Share, 1995) that in typical development learning becomes more implicit in nature after explicit instruction has already taken place. This idea that learning is a blend of explicit and implicit processes is also echoed in developmental models about how children's concepts move from an 'implicit' state to an 'explicit' until their knowledge becomes fully flexible. Karmiloff-Smith (1992) argues in favor of an implicit 'onset' of new representations that are refined and fully developed with the induction of explicit models (Stadler & Frensch, 1998).

To summarize, empirical evidence strongly suggests existence of implicit learning processes. Whether there are separate learning systems that are modular in the sense that they process implicit or explicit information and, if so, the degree to which they might interact is still under consideration. Nevertheless, implicit learning mechanisms seem crucial for many aspects of human learning (Folia *et al.*, 2008). Thus, implicit learning should be further explored to expand our understanding of learning mechanisms in typical and atypical development.

In the following sections, the literature on implicit learning in typical and atypical populations is reviewed. First, the basic criteria and characteristics of implicit learning are introduced together with a discussion of how implicit learning can be defined and researched. The discussion moves on how implicit learning is empirically studied and on the nature of the acquired implicit knowledge. Finally, the empirical findings from typical and atypical populations (across different age groups) will be presented so that a clear developmental picture of implicit learning can be formed.

### 3.3 What is implicit learning?

From the discussion that took place in the previous section, one would expect that implicit learning should optimally be elicited when conscious information is not available (Shanks & St.John, 1994). However, such proposition has received criticism for being futile in the sense that it is impossible to turn off awareness completely. It is very difficult to establish implicit learning merely in terms of the degree of accessibility to conscious awareness (Cleeremans, 1998; Dienes & Berry, 1997; Shanks & St. John, 1994). This difficulty stems from the fact that there is no unitary definition of consciousness as it is a dynamic and multifaceted phenomenon (Cleeremans & Jimenez, 2001).

Although the degree of awareness has initiated considerable debate (e.g. Cleeremans, 1997; Shanks & St.Johns, 1994; Perruchet & Pacteau, 1991) it is still a recurring defining feature. Reber (1989) for example, proposes that implicit learning is present when (a) the sum of unconscious information is greater than (b) the sum of the conscious information, available to the subject at a given time (i.e. $a_x > b_x$ , where x is any given time). According to Dienes (2004) on the other hand, implicit learning can be established when the acquired knowledge cannot be explicitly recalled and people believe they are guessing. He states: "… implicit knowledge is knowledge not consciously activated at the time of a cognitive process. Empirically, A is implicit if we believe we are guessing, and A is explicit if we are aware of any degree of knowing A" (Pothos, 2007, p.230).

From the aforementioned examples, it becomes evident that the term *implicit* has a dual nature: it refers both to the process of learning as well as the content of learning. Most of the implicit learning research focuses on the learning product rather than the process *per se* despite the fact that the majority of the existing definitions highlight the properties of both the process and the resulting knowledge.

However, all definitions of implicit learning seem to follow three basic criteria, which in turn, shape the way research in implicit learning is conducted. The proposed criteria are pragmatic in the sense that they facilitate a firmer distinction between explicit and implicit learning; those are (a) the incidental character of learning (i.e. the inability of the learner to use hypothesis- testing methods), (b) the conscious inaccessibility of the acquired knowledge reflected in the lack of the ability to verbalize it, and (c) the complexity of the information to be learned.

To satisfy the first criterion for implicit learning, the learner is passive towards the learning that is about to take place. The lower the threshold of awareness of the underlying structure of the stimuli the higher the probability of implicit learning processes being elicited. The learners that deal passively with implicit learning tasks are found to perform equally with or better than (e.g. Dienes *et al.*, 1991, Dulany *et al.*, 1984) participants who try to figure out the exact structure of the task. For example, it has been shown that participants who are given instructions “to pay the utmost attention and to try memorizing” have equal performance with those subjects receiving instructions “to search for rules” and in some cases the ‘naïve’ participants show even better performance (Howard & Ballas, 1980; Reber *et al.,* 1980).

The issue of providing specific information to subjects about the stimuli during implicit learning tasks has been studied in relation to the time of introducing the explicit information (Reber, 1980, 1989) as well as the exact nature of the explicit information (Brooks, 1978; Reber, 1976). The most important finding is that the explicit information is more fruitful when presented at the beginning of the training session as it 'forces' participants to increase their attention towards the relationships among the stimuli (Reber, 1980, 1989). It is likely that this increase in the focus of attention to the present regularities (in the training session) helps participants to implement the proper coding schemes (Reber, 1989). According to Reber (1989) when specific explicit information is presented after the training session, or sometime later on, it 'obliges' participants to form structures that are, in all probabilities, wrong and at the same time disrupts the process that was initiated with the mere observation of the stimuli.

According to the second criterion, implicit learning is also established when learners cannot access the acquired knowledge or are unaware of any degree of knowing (Cleeremans, 1997); they report they are guessing. Empirically, free verbal reports (verbalization criterion) are used as an indicator or as a measure of the degree of accessibility of the acquired information (e.g. Abrams & Reber, 1988; Allen & Reber, 1980; Reber, Kassin, Lewis, & Cantor, 1980). A consistent finding in implicit learning studies is that the participants cannot reflect on the knowledge they have gained despite their above chance performance (see methodology and discussion sections of Chapters 5, 6 & 7). They are not able to report verbally what they have learned. When they claim that they are using information, this information is in most cases invalid or incomplete (e.g. Reber & Lewes, 1997; Posner & Keele, 1968) in the sense that it cannot help them solve the complexity of task.

Another set of studies that tested the verbalization criterion using other techniques and more carefully manipulated experimental conditions (e.g. Dienes & Berry, 1997; Dienes, Broadbent & Berry, 1991; Mathews, Buss, Stanley, Blanchard-Fields, Cho & Druhan, 1989) found that participants use more information during the task than they can report verbally. Shanks (2005) argues that free verbal reports do not provide detailed and/or exhaustive information of the specific kind of knowledge the learners form and therefore cued recall tests should be applied to assess explicit influences. According to Tulving (1983) participants may explicitly store information that they cannot recall under specific test conditions, however, they can make this information available to them when they are given appropriate retrieval cues.

Shanks and St.John (1994) suggest that free reports do not call on all the available explicit knowledge and do not take into account response biases (e.g. Erdelyi, 1974; Holender, 1986; Shanks & St.John, 1994). Instead, they propose another set of criteria to account for implicit learning in response to the verbalization criterion: the information criterion and the sensitivity criterion. They suggest that implicit learning should be closely related to the notions of exclusiveness and exhaustiveness. According to information criterion the tests should elicit the stored knowledge that controls implicit behavior. The sensitivity criterion refers to all conscious knowledge participants hold, which is relevant to the task. To satisfy such criteria empirically, free reports are replaced by cued reports and forced choice tests. However, the objective tests that are widely used fail to fulfill all of the proposed criteria (e.g. it is likely participants give answers for which they are not very confident about). Nevertheless, even if explicit knowledge can be assessed using more sensitive measures, this does not necessarily mean that implicit learning is not present (Cleeremans, 1997).

Dienes and Berry (1997) propose another criterion with two axons: The subjective threshold and the objective threshold. They argue that their criterion resolves the issue of constructing tasks that tap into all available explicit knowledge during implicit learning tasks (the so-called 'contamination problem'). According to Cheesman and Merikle (1984) who first introduced the term, the level that can be used to separate implicit from explicit cognitive procedures is the subjective threshold, which is the point where participants have gained knowledge but cannot reflect upon it; they do not have metaknowledge.

In Dienes and Berry's (1997) account, knowledge is considered to be below an objective threshold when participants give chance responses in tests that are sensitive to the task-relevant conscious knowledge. Knowledge is considered to be below a subjective threshold when participants do not know that they possess knowledge (in the sense that they cannot reflect on this knowledge) although their performance rates are above chance (guessing criterion). The dissociation between their response accuracy and their confidence judgments (zero-correlation criterion) (Dienes & Berry, 1997) can be used an indicator of implicit learning.

The verbalization criterion has received much criticism (Berry & Dienes, 1993; Erdelyi & Becker, 1974; Dienes & Berry, 1997; Shanks, 2005) for being an unsatisfactory account of implicit learning. It is believed that free verbal reports do not take into consideration other factors that could be important, for example, the low confidence rates in participants responding (Dienes & Berry, 1997) or the true amount of available explicit resources (Shanks & St.John, 1994). Other criteria such as the information and the sensitivity (Shanks & St.John, 1994) and the objective and subjective thresholds (Dienes & Berry, 1997) are proposed to more firmly establish implicit learning. However, on empirical grounds, the sensitivity of measures of awareness that are used in terms of exhaustiveness or inclusiveness still remains to be firmly established (Cleeremans, 1997; Cleeremans *et al.*, 1998; Shanks, 2004; Shanks & St.John, 1994). Thus, free verbal reports are still extensively used either solely or in combination with other measures of explicit knowledge.

The third criterion for establishing implicit learning is the complexity of the learning environment. The factors that characterize a complex learning environment can be numerous. The most prominent factors in which implicit learning seems to have an advantage over explicit learning are listed below. However, one has to bear in mind that implicit learning can also be negatively affected by these factors. Moreover, the data so far indicate that implicit learning is less affected under such learning conditions compared to explicit learning; more research is needed to evaluate the degree of influence of such factors on implicit and explicit learning (Seger, 1994).

To begin with, the number of rules to be learned creates a highly complex learning environment. The more rules the learner is faced with the more difficult it is to deal with them simultaneously and use explicit strategies (e.g. Buchner & Funke, 1993;

Hayes & Broadbent, 1988). At the same time the salience of rules affects the use of explicit strategies (see Lewicki, Hill & Sasaki, 1989): if the rules are not theoretically plausible or their surfaces features are very similar then these rules are difficult to be explicitly decoded. Moreover, the presence of random items for which explicit learning cannot easily decide upon (Lewicki, Czyzewska & Hoffman, 1987) and of random noise, which is found to affect explicit but not implicit learning (Cleeremans & McClelland, 1991) are also factors that increase complexity. Finally, indeterminacy that is the stimulus uncertainty (Garner, 1962) caused by the numerous ways one state determines a following state, can also create a complex learning setting.

Implicit learning lends itself to the study of highly complex information (e.g. Hayes & Broadbent, 1988) because explicit learning is sufficient only for the exploitation of simple structures either by spontaneously discovering the patterns or by hypothesis testing. A learning environment of increased complexity is a prerequisite for exploring implicit learning. This last criterion for implicit learning has also a practical function. It can be used as a 'baseline' for the kind of tasks that can be recruited in the study of implicit learning. Implicit learning tasks are presented in more detail in section 3.4 below.

As stated earlier, the purpose of the outlined criteria is to safely distinguish/differentiate implicit learning from explicit learning. However, in real-life learning situations implicit and explicit learning function in parallel or in combination. It is very difficult, if not impossible, to create clear-cut learning settings (or tasks) that tap into implicit learning (Dienes & Berry, 1997) even when these learning settings (or tasks) fulfill those criteria. For that reason, several studies investigate the role of attention[2] in implicit learning to answer whether implicit learning stimuli can be processed with the minimum processing demands; and if so whether this is enough to characterize implicit learning as an automatic process.

Reber (1989) proposes that implicit learning is less affected by the availability of attentional resources and thus, it is more robust in the presence of secondary tasks. He took this further by suggesting that implicit learning would not only be found intact under such learning conditions but also that it would be facilitated. Studies using dual-task conditions (e.g. Dienes *et al.*, 1991) suggest secondary tasks hinder subjects' explicit learning (of simple rules) more than implicit learning (even favor implicit learning in some cases). In most cases, implicit learning performance is unaffected when participants believe they are guessing but their performance is lowered if they have some kind of metaknowledge (Dienes & Berry, 1997; but see also Curran & Keele, 1993).

Yet, there are cases where secondary tasks affect implicit learning (e.g. Cohen, Ivry & Keele, 1990) or do not allow learning to be expressed until these tasks are removed (Reber & Kotovsky, 1992). The studies test Baddeley's (1992) theory of working memory systems (i.e. the degree of involvement of the central executive, the articulatory loop and the visuospatial sketch pad) by using dual-task conditions

[2] There are four meanings of attention relevant to implicit learning theorizing: (1) it refers to conscious processing of stimuli, (2) to automatization (3) to orienting and focusing systems and (4) to different working memory systems (Seger, 1994).

(multi-attentional view of processing) (e.g. Allport, 1989), which theoretically call on different memory systems. In general, the findings suggest that while some implicit learning abilities (e.g. hierarchical and complex motor learning) are affected by dual task interference, others (e.g. simple associations) are not affected (e.g. Curran & Keele, 1993). Central executive (i.e. the 'coordinator' of the other two working memory systems) has been linked with hierarchical learning (see section 3.5.2) and with serial learning of ambiguous sequences (Seger, 1994) (see section 3.5.1).

Altogether, the evidence on the precise amount of conscious processing involved in implicit learning is inconclusive. The degree of attention required to process the stimuli in implicit learning setting is not clear yet. The attentional requirements covary with the tasks that are used: some implicit learning tasks require the minimum attention whereas some others might require more (see section 3.5). Nevertheless, the evidence shows that implicit learning requires at least the minimum of attention in terms of the cognitive processing of the stimuli. But, is this minimal attention enough to characterize implicit learning an automatic process?

Early definitions of automaticity (Hasher & Zacks, 1979) pose a set of strict criteria, for example, an automatic system must not call for other cognitive processes or benefit from practice. According to this stringent view of automaticity, implicit learning cannot be considered automatic: implicit learning engages other cognitive processes while performance improves through extensive practice (Seger, 1994). However, more recent modified definitions of automaticity (e.g. Sander, Raymond, Gonzalez, Murphy, Liddle & Vitina, 1987) suggest that the most important features of automaticity are learning under minimum attention and incidental conditions. Implicit learning sits comfortably in this view of automaticity because (a) it requires the minimum attentional resources and (b) it is incidental. Consequently, implicit learning can be considered an automatic process (Seger, 1994).

### 3.4 Research paradigms to explore implicit learning

The research paradigms that are used in the study of implicit learning fit the criteria for implicit learning as described in the previous sections. For example, the paradigms create incidental learning conditions by not providing any direct instructions that contain information about the underlying regularities of the stimuli. Also, the paradigms use stimuli that are not salient in the sense that they are not meaningful so, participants cannot use any previously acquired knowledge to meet the demands of the task. Finally, the tasks use numerous rules to create highly complex stimuli so that hypothesis testing is difficult to apply (Fletcher *et al*., 2000) to resolve the tasks' complexity. It has to be stressed that there are no tasks tapping into pure implicit or explicit processes (Orban *et al.*, 2008), however, the experimental manipulation of these tasks can maximize the induction of either implicit or explicit learning (see Chapter 5).

Seger (1994) outlines the types of stimuli and the response modalities that the implicit learning paradigms utilize. The paradigms use three types of stimuli; visual patterns; sequences; and functions. They also engage three response modalities: conceptual fluency (where participants are asked to rate or classify items based on gut feeling), efficiency (where participants' learning is reflected in the increase of speed or accuracy in the presence of items) and prediction/control (where participants show learning by either making accurate predictions about or controlling over aspects of the items). Stimulus types and response modalities tend to covary (e.g. sequences are usually tested through efficiency). Yet, this covariation is not normative in the sense that there are cases where different stimulus types are evaluated through different response modalities (e.g. Deroost & Soetens, 2006).

The paradigms employed are usually composed of three parts. In the first part, participants are exposed to complex stimuli that obey particular rules but without participants being given any directions to intentionally learn the rule-governed nature of the stimulus set. In the second part, participants are asked to perform a 'recognition' or 'decision' test of new items that either follow or violate the structure of the items presented during the first part. Performance on this test is used as a measure of any learning that took place in the first part (i.e. how well participants have encoded the rule-governed environment that they had been previously exposed to). In the third part, participants are given a measure of conscious accessibility of the knowledge that is formed during the task, for example, post-experimental interviews (free verbal reports), forced-choice tasks (i.e. participants are given incomplete items and are asked to complete the missing elements), recognition tasks (i.e. participants are shown parts of a sequence and asked to decide whether these parts correspond to parts of training items) (e.g. Destrebecqz, Peigneux, Laureys, Degueldre, Fiore & Aerts, 2005) and generation tasks (e.g. Destrebecqz *et al.*, 2005).

Several experimental paradigms seem to satisfy the criteria for establishing implicit learning as outlined in section 3.3, such as the Incidental Covariation Paradigm (e.g. Posner & Keele, 1968), the Control of Interactive Systems (Berry & Broadbent, 1984; Hayes & Broadbent, 1988), the Serial Reaction Time Task (SRTT) (e.g. Nissen & Bullemer, 1987), the Artificial Grammar Learning (AGL) (e.g. Dienes & Berry, 1991; Reber, 1967) or the Hebb digit tasks (Hebb, 1961). However, the most widely used paradigms in both typical and atypical populations are the SRTT and the AGL. The following section presents a brief account of these two paradigms.

### 3.4.1 Serial reaction time (SRT) paradigm

Serial reaction time tasks are frequently used in the study of implicit learning. Nissen and Bullemer (1987) were the first to introduce this paradigm in which participants are confronted with stimuli presented to them serially and are asked to respond by pressing a corresponding key to each of the four quadrants of a screen. In the original paradigm (Nissen & Bullemer, 1987) participants were divided in to two groups: The first group is exposed to random sequence of appearing stimuli. The second group is exposed to structured sequence of appearing stimuli. In more recent versions of the task the stimuli are presented in different ways to participants. In some cases the stimuli are arranged in blocks; some blocks contain sequences of stimuli that follow a fixed repeated order (usually ranging from eight to twelve elements long) whereas the rest of the blocks random sequences. In other instances, the structured stimuli are disrupted by ‘deviants’. These are single stimuli or responses that are placed in positions that interrupt the fixed stimuli.

Participants are not informed about the structured nature of some of the stimuli. Although participants are unaware of whether a stimulus follows a fixed order or not, they tend to respond gradually faster and more accurately during the structured blocks. Reaction times and response errors are taken as an indicator of sequence-specific learning (Meulemans, Van Der Linden & Perruchet, 1998). Therefore, in many designs of serial reaction time tasks (SRTT), implicit learning is the difference in performance for structured versus random blocks or for standard versus deviant trials.

Perlman and Tzelgov (2006) argue that it is critical to break down sequence learning into knowledge acquisition and knowledge retrieval respectively so that empirically one can distinguish between the learning (and consequently a potential 'learning problem') and its expression (and a potential 'performance problem'). Given that a variety of SRTT can be created by applying different formats of stimuli and responses (e.g. verbal or spatial stimuli and verbal or spatial responses in all combinations) different inferences could be made in relation to implicit sequential learning and performance. Stimulus and response type as well as the compatibility between task items and their response are considered important factors in the detection of implicit learning.

Findings from dual-task SRTT experiments (Frensch *et al*., 1998; Frensch, Wenke & Runger, 1999) suggest that not all forms of SRTT allow the detection of implicit learning: low reaction times may only reflect an inability to detect implicit learning in performance and not an implicit learning deficit *per se*. In other words, some SRT tasks may not be sensitive enough to detect the implicit learning that takes place. By the same token, studies suggest that spatial stimuli and compatible location of the sequence are more likely to induce implicit learning in a more pronounced way (e.g. Hoffmann & Koch, 1997; Koch & Hoffmann, 2000). Conversely, other studies suggest that the incompatibility in stimulus-response mapping enhances implicit learning (e.g. Deroost & Soetens, 2006; Frensch & Miler, 1995).

Another set of studies using the SRTT with concomitant dual-task conditions (Cohen *et al.*, 1990; Keele & Jennings, 1992; McDowall, Lustig & Parkin, 1993; Nissen & Bullemer, 1987) suggest that implicit serial learning can be explained by some degree of explicit learning of the sequences (Curran & Keele, 1993). Studies (Tubau & Lopez-Moliner, 2004; Wilkinson & Shanks, 2004) advocate an interaction between implicit and explicit processes during SRTT but other research (e.g. Willingham, Nissen & Bullemer, 1989) has also demonstrated that implicit learning is induced even if subjects are partially aware.

The SRTTs have been used extensively to explore implicit motor sequence learning following the assumption that these tasks tap mostly into implicit processes (Orban, Lungu & Doyon, 2008). However, there seems to be a mixture of implicit and explicit learning processes during serial reaction tasks (e.g. Destrebecqz, Peigneux, Laureys, Degueldre, Del Fiore, Aerts, *et al*., 2005) depending on the nature of instructions (i.e. incidental, Meulemans *et al*., 1998 or intentional), the structure of the sequences (i.e. deterministic or probabilistic, Willingham & Goedert- Eschmann,

1999) and the experimental/administrative regime (i.e. the presentation of training stimuli, the response-to-stimulus interval, Destrebecqz *et al.*, 2005). For example, deterministic sequences (i.e. when one element in a preceding stimulus predicts precisely the appearance of the next stimulus) are thought to facilitate the emergence of explicit learning whereas probabilistic sequences (where one preceding element can determine multiple following stimuli appearances) that of implicit learning. Therefore, any inferences about implicit learning (or explicit) and the resulting knowledge should be made carefully and in accord with the underlying processes that the particular features of a serial task activate.

### 3.4.2 Artificial grammar learning (AGL) paradigm

AGL has been primarily used in the debate about what kind of knowledge participants acquire during implicit learning tasks (i.e. on knowledge format and representation) and has immensely affected the theoretical frameworks of knowledge representation (see section 3.6; but also see Pothos, 2007 for a comprehensive review). The acquisition of complex information without awareness has been explored in earlier work on concept formation and categorization. The construction and use of synthetic and semantic-free grammars known as 'Markovian grammars' provide the ground for the construction of the artificial grammar learning paradigm to study implicit learning (Reber, 1967).

A finite state language with arbitrary rules (i.e. only certain continuations are permitted) is used to generate the stimulus set. This finite state grammar divides the stimuli according to those that follow allowed transitions (grammatical stimuli) and those that do not (non-grammatical stimuli). The grammatical items are always fewer than the non-grammatical (Pothos, 2007) as the violations that one could make to the permissible transitions are free from many constrains (e.g. there is not a predetermined position that you are allowed to violate in the grammar to construct the non-grammatical items). In a typical AGL task participants are shown stimuli that are constructed based on a particular grammar and then they are asked to identify which of the new sequences are compatible with old sequences (Pothos & Bailey, 2000) that is, to make grammaticality judgments on whether the new strings are "legal" or "illegal" according to the old ones.

The paradigm is divided into two parts. In the first part, the training phase, participants are required to either pay their utmost attention or to try and memorize a set of training stimuli that conform to the grammar in use. However, no further information is provided about the rules that underlie the structure of the presented stimuli. In the second part, the testing phase, they are exposed to a new set of stimuli (some of them grammatical and some of them non-grammatical) and they are asked to make grammaticality judgments. Successful completion of the task (i.e. correct classification on test items) indicates participants have implicitly acquired new information. A consistent finding in the relevant literature is that participants tend to classify correctly the new sequences while they exhibit the 'archetypal implicit learning effect' (Redighton & Chater, 1996): they are unable to articulate the knowledge they use to perform their grammaticality judgments despite the fact that their performance is above chance level.

There are a number of critical features of AGL tasks that are salient in the identification of implicit learning being present and which in turn explain their extensive use in the relative research literature. The complexity of the grammar rules is so high that it cannot be accessed through the engagement of conscious memorial efforts, while the participant is bound to produce an amount of knowledge in order to be able to respond with a degree of accuracy during the testing phase (Reber, 1989); in other words, they must induce some implicit knowledge to make correct grammaticality judgments. If the use of conscious attempts can solve the stimulus complexity then it is difficult to assess the emergence of implicit processes; participants should not be able to use conscious code-breaking strategies (Reber, 1989; Lewicki, 1987).

The finding that amnesic patients, who have deficits in explicit learning (e.g. deficient activity of the hippocampus), are found intact in AGL tasks (Knowlton & Squire, 1994, 1996; Knowlton, Ramus & Squire, 1992) adds weight to the implicit character of AGL. Similarly, data from dual-task AGL settings (Dienes, Broadbent, & Berry, 1991) indicate that implicit learning takes place even when dual-tasks interfere. However, implicit learning is experimentally detectable only when the dual-task conditions are removed (Seger, 1994). Based on the particular dual tasks that are used (e.g. random number generation, Dienes *et al.*, 1991) the data also suggest that the central executive and to a lesser extent the articulatory loop may be mediating AGL learning but more research is needed to fully explore this interference.

However, the degree of interaction between implicit (Ashby, Alfonso- Reese, Turken, & Waldron, 1998; Reber, 1993; Sperling *et al.,* 2004) and explicit learning processes (Dulany, Carlson, & Dewey, 1984; Perruchet & Pacteau, 1991) during AGL performance is not yet very clear. For example, there are instances where the change in the nature and circumstances of presentation of the set of instructions has been found to facilitate (Howard & Ballas, 1980; Reber *et al.,* 1980) or diminish performance (Brooks, 1978; Reber, 1976). Despite that, the inherent complexity of the AGL tasks seems to create learning conditions that are largely unintentional (i.e. they require the minimum attentional resources and are automatic) facilitating this way the induction of implicit learning processes.

### 3.5 Cognitive and neural basis of implicit learning

The use of the SRT and the AGL paradigms in the research of implicit learning has produced substantial behavioral evidence towards the exploration of the important issue of the nature of implicit learning. Whether implicit learning is 'amodal' (i.e. a single learning system served by a domain-general mechanism) or whether implicit learning constitutes multiple learning systems (i.e. independent subsystems being responsible for processing stimulus-specific information) (Conway & Pisoni, 2008) remains unresolved.

The majority of behavioral studies provide evidence in favor of 'an amodal' view of implicit learning. Implicit learning is established in studies that use different stimuli including tones (e.g. Saffran, Johnson, Aslin & Newport, 1999); shapes (Pothos & Bailey, 2000; Pothos & Kirk, 2004); and speech-like sounds (e.g. Gomez & Gerken, 1999). In parallel, studies establishing transfer of implicit learning across different stimuli (e.g. Altmann, Dienes & Goode, 1995; Brooks & Vokey, 1991) add weight on the amodal and abstract nature (Conway & Pisoni, 2008) of implicit learning. Pothos and collaborators (2006) demonstrate by utilizing 3 types of stimuli (strings of letters, shapes and cities) with the same underlying rule system that the induction of implicit learning seems to be independent of stimulus appearance (Reber, 1993).

Recently however, the amodal nature of implicit learning is questioned by the work of Conway and Christiansen (2006, 2005) who study implicit artificial grammar learning in different modalities (i.e. tactile, visual and auditory). So far, the results from their studies suggest qualitative differences in implicit learning between the modalities. Although implicit learning is manifested across all three modalities, performance in the auditory AGL task is higher compared to other modalities (Conway & Christiansen, 2005). Driven by those findings, Conway and Christiansen (2006) explored implicit learning across and within modalities and within the same perceptual dimension. Their results suggest that implicit learning can be induced in two input streams (Conway & Pisoni, 2008) as long as different sense and perception modalities are engaged. They argue this pattern of results serves as an indicator of the existence of multiple mechanisms (Conway & Christiansen, 2006).

Taken together the data suggest that implicit learning depends on a wide range of brain areas that are activated in different degrees depending on the nature of the input, the tasks demands and the learning setting (Conway & Pisoni, 2008). Yet, specific neural circuits are studied separately in populations that have impairments in those areas to reveal the degree of their involvement in implicit learning. Data from neuroimaging studies on various clinical populations (e.g. amnesic patients, Parkinson's, Huntington's and Alzheimer's patients) during implicit learning tasks implicate subcortical areas such as the basal gaglia[3] (e.g. Siegert, Taylor, Weatherall & Abernethy, 2006 as cited in Conway & Pisoni, 2008), the cerebellum (e.g. Paquier & Marien, 2005), the medial and temporal parietal lobes (Kosslyn & Koenig, 1992), and the frontal lobes (e.g. Janowsky, Shimamura & Squire, 1989; but see also Leonesio & Nelson, 1990). There is also neuroimaging evidence that more specific (i.e. modality-specific) areas of brain such as the occipital cortex (e.g. Forkstam *et al.*, 2006; Lieberman, Chang, Chiao, Bookheimer & Knowlton, 2004) are also implicated in implicit learning.

On the whole, implicit learning seems to be mediated by both specific and general neurocognitive mechanisms, which in turn engage a wide range of brain areas that are coordinated. This finding raises the question of whether the product of implicit learning (i.e. the mental representation of implicit knowledge) depends on the format of the stimuli and the sensory modality through which they are presented to the learner. The following section outlines what has been proposed so far to account for implicit knowledge in an attempt to reach some conclusions about the kind of representations the learner is constructing in implicit learning settings.

## 3.6 What kind of knowledge do we acquire implicitly?

[3] Support for the involvement of basal gaglia in implicit learning comes also from studies on habit learning in animals (e.g. Wang, Aigner & Mishkin, 1990) although animals seem to rely on different learning mechanisms compared to humans (Squire, 1992).

Reber's (1967) initial claim that implicit knowledge is abstract and unconscious has raised considerable debate (see Berry & Dienes, 1993; Seger, 1994; Shanks & St.John, 1994 for reviews) initiating research on the representational structure of implicit knowledge (i.e. whether implicit knowledge can be described as abstract rule- like or as of specific instances) (Redington & Chater, 1996). Specifically, research explores if learners acquire knowledge that is in the form of (a) abstract rules; (b) whole stimuli (i.e. verbatim) and; (c) partial stored stimuli (i.e. aggregate) (Stadler, 1992 as cited in Seger, 1994). However, to be able to draw some preliminary conclusions over the form of implicit knowledge, it is important to clarify what abstraction means in the context of implicit learning and how/if it relates to instantiation (i.e. the dependence of knowledge on the surface characteristics of the stimuli).

There are three main notions of abstraction relevant to implicit learning theory. In the first notion abstraction is connected to the level of interpretation of the displayed stimuli and is catholically accepted: In the case of AGL for example, letters will be abstracted as letters (Redighton & Chater, 1996). The second notion concerns surface properties of each training item. When a particular item is not efficiently encoded but only parts or fragments of it, the participant becomes sensitive to the underlying structure due to abstract mechanisms that are elicited. In the same AGL example, because grammatical items contain more permissible element combinations compared to non-grammatical ones (Redighton & Chater, 1996) they are likely to induce abstraction. According to the third notion, abstraction is present when the underlying structure of old items can still be transferred to novel items that have different instantiation (i.e. different surface characteristics). In other words, abstract knowledge is considered to be the ‘syntax’ while the surface items in use are the ‘vocabulary’.

It has been suggested (e.g. Gick & Holyoak, 1980) that participants in implicit learning tasks will not be able to use (transfer) their knowledge if the cues are not there or have completely changed. However, in many of the findings from transfer experiments (in which learners show evidence of transferring knowledge to stimuli that have different surface characteristics but share the same deep structure) participants are able to transfer their knowledge into a new task (Altmann *et al*., 1995; Gomez & Schvaneveldt, 1994; Manza & Reber, 1994; Whittlesea & Dorken, 1993). The transfer effect is used as marker of abstraction (e.g. Altmann *et al.*, 1995; Gomez & Gerken, 1999; Redington & Chater, 1996) that adds weight to the amodal and independent nature of implicit learning (i.e. implicit knowledge is considered of the surface characteristics of the stimuli, Conway & Pisoni, 2008). However, transfer is not firmly established in all implicit learning paradigms (Orban *et al.*, 2008). The degree of transfer in SRTT is not clear yet (Seger, 1994). Moreover, abstract learning representations do not necessarily rule out the possibility of partially instantiated co-existing knowledge (Seger, 1994).

Artificial grammar learning is considered a key paradigm for testing how implicit knowledge is represented mentally. In the relative literature we come across exemplar-based accounts of the acquired knowledge (Brooks, 1978; Brooks & Vokey, 1991; Vokey & Brooks, 1992) as well as fragment- based (Perruchet &

Pacteau, 1990, 1992) and abstract knowledge acquisition accounts (Dulany, Carlson & Dewey, 1984, 1985; Reber, 1969; Manza & Reber, 1994). For example, Brooks and Vokey (1978, 1992, 1994) propose that grammaticality judgments are primarily based upon the similarity of the displayed test item to the memorized training item[4] while Perruchet and Pacteau (1990, 1992) suggest that these grammaticality decisions are based upon the comparison between the memorized chunks (in the form of two (bigrams) or three (trigrams) legal combinations) encountered at the training set and the novel ones. Finally, rule-based theory accounts suggest that individuals acquire the underlying structure of the stimuli (Reber, 1969; Manza & Reber, 1994) or a set of postulated "microrules" (Dulany *et al*., 1984, 1985) that can account for the above chance performance in AGL tasks.

Subjects are found to be sensitive to specific item factors such as the similarity of testing items to training items (Vokey & Brooks, 1991, 1992), fragment information (Dulany *et al*., 1984) or bigram information (Perruchet & Pacteau, 1990). However, the proposal that participants use a process of analogy to stored items to implicitly learn visually presented items is in direct contrast with the 'nonhippocampal view' of implicit learning (as supported by data from amnesic patients where implicit learning is preserved despite poor explicit memory). Bigrams on the other hand, can account for a large amount of information participants acquire but they do not account for other factors such as the sensitivity to positional dependencies in artificial grammars (Seger, 1994).

[4] For a detailed account of similarity effects in AGL tasks see Pothos & Bailey (2000).The role of similarity in Artificial Grammar Learning. *Journal of Experimental Psychology: Learning, Memory and Cognition*, *26 (4),* 847-862.

Overall, the empirical data suggest that participants in implicit learning tasks acquire more information about the items than whole exemplars or bigrams. Thus, it can be said that participants acquire more abstract knowledge but it is not clear yet whether this abstract knowledge is tied to surface characteristics of the items to be learned; the data on the amodal or modality-specific nature of implicit learning is mixed. At the same time, the transfer effect comes as support for abstract rule-learning accounts; but transfer phenomena do not necessarily mean that the resulting knowledge is stored in the form of abstract rules (Redington & Chater, 1996). Because the issue of knowledge representation is still a matter of debate, it is more reasonable to suggest that participants may acquire some kind of explicit knowledge that co-exists with the implicit knowledge (i.e. largely abstract) (Perruchet & Pacteau, 1991; Dulany *et al*., 1984) depending on the general task characteristics that can facilitate either types of learning.

### 3.7 Summary

Following Seger (1994) and Forkstam & Petersson (2005) this thesis adopts the following criteria/characteristics of implicit learning: (a) learners have restricted explicit access to the acquired knowledge that is reflected in their inability to provide a detailed explicit account; (b) implicit learning is an automatic (incidental) process that does not entail hypothesis testing strategies; (c) learners acquire complex knowledge; and (d) the acquired knowledge is largely abstract provided that the task format facilitates the emergence of abstraction mechanisms.

Cleeremans *et al*. (1998) propose that research should opt for a functional approach of implicit learning. Empirically, this functional approach (a) refers to hypothetical learning processes that are taking place during the task (i.e. explicit or implicit learning); (b) tries to control for factors such as the intention to learn or the amount of available attentional resources (e.g. Frensch, Buchner & Lin, 1994) and; (c) employs different measures either direct or indirect to assess learning. The direct measures of learning tap into participants' conscious knowledge that is relevant to the task whereas the indirect measures tap into knowledge that it is not consciously prompt or explicitly asked during task performance.

Following Cleeremans *et al*. (1998) and for the purposes of this thesis, implicit learning is thought to be the automatic, unintentional (Perruchet & Pacteau, 1991) (possibly without awareness) learning (Pothos, 2007) that takes place when people are faced with complex information and which results in knowledge that it is difficult to express (Cleeremans, 1998). This definition is sufficient to serve the purposes of this thesis in terms of the choice of the experimental regime and the interpretation of the empirical findings (see Chapters 5, 6 & 7). This thesis will not argue that any one definition of implicit learning is correct (or incorrect). Instead the choice of a particular definition summarizes the framework of understanding and exploring implicit learning.

### 3.8 Implicit learning across development

But at what point do these implicit learning skills emerge? Studies on infant learning (e.g. Clohessy, Posner & Rothbart, 2001; Gomez & Gerken, 1998; Marcus et *al*.,

1999) show that implicit learning abilities are already well-established in infancy compared to less well-developed explicit learning abilities at this age. This adds weight to the evolutionary account of the primacy of implicit learning over explicit learning (Reber, 1989).

However, moving on to childhood the efficiency of implicit learning abilities shows a subtle variance according to age (Clohessy *et al*., 2001; Thomas & Nelson, 2001) and intellectual level (Fletcher *et al*., 2000; Maybery *et al.*, 1995), with older and more cognitively advanced children doing better than younger and intellectually less advanced children in implicit learning tasks. In spite of the aforementioned subtle variance implicit learning is usually found functioning at a high level in 'typical' childhood. Accumulative behavioral and neuroimaging data (e.g. Thomas, Hunt, Vizueta, Sommer, Durston, Yang & Worden, 2004) from children and adults provide evidence of age differences in implicit learning. The findings also suggest that adults perform higher in implicit learning tasks compared to children. At the same time, the neuroimaging data point to the possibility of the existence of different implicit and explicit learning systems; those systems being sub-served from distinct neural networks that are activated in different specific locations and degrees according to age (Thomas *et al.*, 2004).

Implicit learning is thought to be more robust in the face of psychological and physiological dysfunctions, of individual differences (e.g. age and intellectual ability) and of secondary tasks (Dienes & Berry, 1997). Support for the psychological and physiological robustness of implicit learning comes from studies in different patient populations: (a) amnesic patients (Knowlton, Ramus & Squire, 1992; Knowlton & Squire, 1994, 1996); (b) patients with Alzheimer (e.g. Kopman & Nissen, 1987; Grafman, Weingartner, Newhouse, Thompson, Lalonde, Litvan, Molchan, Sunderland, 1990); (c) patients with schizophrenia (Danion, Meulemans, Kauffmann-Muller & Vermaat, 2001) and; (d) patients with Williams syndrome (Don, Schellenberg, Reber, DiGirolamo & Wang, 2003). In the majority of these studies implicit learning abilities are found intact in populations that have significantly impaired explicit learning abilities.

The literature in IQ and age effects on implicit learning, however, is less consistent. Studies conducted in various populations have yielded equivocal results. There is a set of studies that supports the claim for IQ and age invariance in implicit learning (e.g. Vinter & Perruchet, 2000; Meulemans *et al*., 1998). On the other hand, another line of studies (Thomas & Nelson, 2001; Fletcher *et al.*, 2000; Maybery *et al.*, 1995) provides evidence for developmental influences in implicit learning related to age and intellectual abilities: Older and more intellectually advanced children tend to do better in implicit learning tasks than younger and less intellectually advanced children.

If individual differences influence implicit learning, then very important inferences could be made in relation to typical and atypical development. For example, there is an ongoing dispute in the reading disorder literature on whether garden-variety poor readers (i.e. poor readers of various cognitive abilities) differ significantly on various linguistic and non-linguistic tasks with dyslexic readers (Stoodley *et al*., 2008). Implicit learning could provide the empirical ground to test different hypotheses regarding reading-impaired populations such as individual with developmental dyslexia especially given the proposed relationship of implicit learning with competent reading. The following section discusses how implicit learning is implicated in reading and sets the ground for the empirical work that will be presented in following chapters of the thesis.

### 3.9 Implicit learning and reading

Reading is a good example of the way implicit learning can play a distinctive role along with explicit learning (Gombert, 2003; Rayner, Foorman, Perfetti, Pervesky & Seidenberg, 2001; Sperling, Lu & Manis, 2004). There is a rather general agreement (Ellis, 2005; Alexander & Slinger-Constant, 2004; Reder & Allen, 2000; Torgesen *et al*., 2001) on the importance of explicit instruction (e.g. learning of rules or phonological training) in the acquisition of good phonological skills and consequently in learning to read. However, it is also widely accepted (e.g. Ehri, 1990; Gombert, 2003; Harm & Seidenberg, 2004; Share, 1995; Sperling *et al*., 2004) that successful reading involves a range of both explicit and implicit learning abilities.

Ashby and Maddox (1993) argue that in the early stages of development implicit learning may affect the maturation of successive abilities involved in reading such as elementary auditory and articulatory skills, eye movements and letter recognition. Bitan and Karni's (2003) study is in support of implicit learning influences in reading-related abilities. Based on their empirical data, Bitan and Karni (2003) suggest that implicit whole-word training leads to the gradual development of letter decoding independently of explicit letter knowledge. Therefore, implicit learning seems to contribute to reading-related abilities such as word-specific recognition or letter knowledge along with explicit learning.

The search for regularities (i.e. the application of statistical rules) (Sperling *et al*., 2004; Howard *et al*., 2005) and the organizing and integration of complex information in a structured environment such as reading is considered to be the primary perceptual intuition (Pothos & Kirk, 2004; Saffran, Newport, Aslin, Tunick & Barrueco 1997; Saffran, Johnson, Aslin & Newport, 2001). According to Cassar and Treiman (1997) children induce implicit learning prior to explicit learning as far as print is concerned; they show a degree of sensitivity in non-explicitly taught orthographic regularities (Cassar & Treiman, 1997). Children also seem to show an increased sensitivity to structural features (Combert, 2003) that are related to the written system. In similar vein, Sperling and collaborators (2004) state reading fluency is mastered with a mixture of explicit learning and implicit learning even in languages that are highly regular in grapheme-phoneme correspondences. Connectionist models simulation results (e.g. Harm & Seidenberg, 1999, 2004; Seidenberg & McClelland, 1989) bolster the argument that any attempt to attain reading fluency probably involves implicit learning procedures (Sperling *et al*., 2004).

It follows that deficits in implicit learning abilities in childhood may affect negatively the expected reading growth despite intact explicit learning abilities.

Implicit learning becomes relevant to the study of children with atypical developmental profiles such as those children with developmental dyslexia given that there are persisting problems (e.g. poor reading in terms of speed/fluency) even in cases where good explicit abilities can be established (see section 4.2). An implicit learning deficit could prevent orthographic-phonological mappings and good phonological skills from being fully established (Sperling *et al.*, 2004) reflected in poor reading.

### 3.10 Summary and Discussion

As illustrated in the review, implicit learning has raised controversy mainly due to its close relationship with the notions of awareness and accessibility of knowledge. To resolve this controversy a number of criteria and properties have been proposed to create a framework in which to think about implicit learning and at the same time to qualitatively distinguish it from explicit learning.

To date, the empirical evidence show that participants perform well in implicit learning tasks without being able to report verbally what they have learned or why they made those decisions (Dienes & Berry, 1997). In cued tests, however, participants give more information about what they have learned. Since this knowledge becomes available to the participants then, it is in all probabilities conscious (Shanks & St.John, 1994). But with the use of the subjective and objective thresholds this information can be viewed as being both implicit and explicit depending for example, on how confident participants are in their responses and the degree of metaknowledge they have (Dienes & Berry, 1997).

Overall, the way implicit learning is viewed depends on the criteria and properties that are used each time to define it. However, these criteria and properties are only indicators of internal or external processes, as we don't have insight of these processes when they are taking place. Therefore, we need to be very careful about the way we interpret the data and at the same time, incorporate alternative methodologies.

Empirically, the vast majority of studies on implicit learning were done on adult populations resulting in supporting evidence of a relative stability of implicit learning processes across adulthood (for a review, see Reber & Allen, 2000). Only a few studies were conducted on younger populations (infants or children). The two major inferences (or assumptions) that implicit learning abilities are well developed in early childhood and that they are robust in a wide range of intellectual abilities were mainly derived from research on adults, which raises the issue of whether these inferences can be safely made for children who share a different developmental profile.

However, to be able to safely conclude that implicit learning is well adopted early in development and that it is invariant to individual differences, we need to further explore implicit learning in populations with different developmental profiles. We need to control for different factors that could affect implicit learning processes so that we have a fuller picture of how implicit learning abilities develop. In a similar vein, studying implicit learning in developmental dyslexic populations (who share a different developmental profile compared to that of typically developing populations) may offer the ground for exploring how different developmental factors may affect implicit learning. In turn, the investigation of implicit learning abilities in developmental dyslexic populations can highlight how non-linguistic learning abilities underlie linguistic abilities in reading impaired populations. In keeping with this viewpoint, a very limited number of studies have focused on the relationship between implicit learning in developmental dyslexia. In the next chapter, this thesis reviews the literature on developmental dyslexia and implicit learning illustrating how their combined study can inform the conceptualization of developmental dyslexia and in turn, of implicit learning.

# CHAPTER 4

# DEVELOPMENTAL DYSLEXIA AND IMPLICIT LEARNING: 'NEW CROP FROM OLD FIELDS'

## 4.1 Aims of Chapter

The current chapter reviews the limited work that combines research on implicit learning (presented in Chapter 3) and developmental dyslexia (presented in Chapter 2). It highlights the fact that in contrast to the extensive literature on specific explicit learning abilities, the literature on implicit learning abilities in children with developmental dyslexia is piecemeal and has produced controversial findings. As the literature review will illustrate, the predominant use of the serial reaction time (SRT) paradigm in the study of implicit learning abilities and the inferences about children drawn from adult studies, compromise our wider understanding about how these abilities develop in children with an atypical developmental profile such as children with developmental dyslexia.

## 4.2 Introduction

There is a consensus (see Chapter 2) that people who are diagnosed with developmental dyslexia experience reading problems that have an onset in childhood and in many cases persist into adulthood. The phonological theory (i.e. that an impairment in the processing and representation of phonological information underlies dyslexia) is extensively used to account for the noted reading difficulty in developmental dyslexia (e.g. Harm & Seidenberg, 1999; Rayner *et al*., 2001; Share, 1995). However, there are instances where people with developmental dyslexia exhibit satisfactory performance on standard phonological tests (Brunswick *et al.*, 1999; Nicolson & Fawcett, 1990) but fail to achieve fluency in reading (Paulesu *et al*., 2001; Wimmer, 1993; Wimmer *et al*., 2000). In other words, they face problems with recognizing word fluently despite good explicit knowledge of grapheme-phoneme correspondence (Sperling, Lu & Manis, 2004).

This dissociation between good specific abilities and well-developed reading raises the possibility that learning to read has common features with other types of skill learning. The view that general non-linguistic learning abilities could mediate fundamental reading mechanisms (e.g. Nicolson & Fawcett, 1999; Stein & Walsh, 1997; Stein, 2001) has increased interest in implicit learning. Many authors (e.g. Gombert, 2003; Share 1995; Sperling *et al*., 2004) claim that reading involves a blend of explicit and implicit learning abilities so, any deficits in any of these abilities may prevent learners from becoming fluent readers.

By the same token, there is a line of research into implicit learning abilities in developmental dyslexia (Howard, Howard, Japikse & Eden, 2006; Kelly, Griffiths & Frith, 2002; Pothos & Kirk, 2004; Roodenrys & Dunn, 2007; Russeler, 2007; Stoodley, Harrison & Stein, 2006; Stoodley, Ray, Jack & Stein, 2008; Sperling *et al*., 2004; Vicari, Marotta, Menghini, Molinary & Petrosini, 2003; Vicari, Finzi, Menghini, Marrota, Baldi & Petrosini, 2005; Waber, Marcus, Forbes, Bellinger, Weiler, Sorensen & Curran, 2003). The aim of these studies is to explore how implicit learning abilities relate to the cognitive and neural basis of developmental dyslexia and whether or not potential implicit learning deficits have a share in the etiology of developmental dyslexia.

Overall, the limited findings from older and younger populations, namely university students and primary school children, are controversial. The few studies that have been published explore how implicit learning, which is considered an automatic process (see Chapter 3, section 3), is linked to automatization in developmental dyslexia (Nicolson & Fawcett's, 1990, 1995) and in turn, to fluent reading. The studies examine how implicit learning deficits can compromise reading skills in developmental dyslexia and *vice versa*; developmental dyslexia could hinder implicit learning mechanisms mediating successful reading. The choice of a particular implicit learning task is guided by assumptions about either (a) the brain areas activated during performance that have been associated with the functional pathology of developmental dyslexia (e.g. Nicolson, Fawcett, Berry, Jankins, Dean & Brooks, 2001; Zeffiro & Eden, 2001) or; (b) the specific implicit learning processes each task is designed to tap into (e.g. Vicari *et al*., 2005, see also Chapter 3, section 4).

All the studies to date on implicit learning and in developmental dyslexia use either the serial reaction time (SRT) or the artificial grammar learning (AGL) paradigms. AGL and SRTT paradigms are used in their original form or in an alternated one in terms of procedure manipulations (Vicari *et al*., 2003; Howard *et al*., 2005) and stimulus format (Pothos & Kirk, 2004; Sperling *et al*., 2004). They are also used on their own (Kelly *et al*., 2000; Stoodley *et al*., 2006; Vicari *et al*., 2003) or in combination with another implicit learning paradigm (Vicari *et al*., 2005; Howard *et al*., 2006; Russeler, 2007).

### 4.3. The research data

In the following sections, a comprehensive review of this small research corpus on adults and children with developmental dyslexia is presented separately. The review will contrast the research on developmental dyslexia and the research on implicit learning in typical populations (discussed in more detail in Chapter 3). The extremely limited data on implicit learning and developmental dyslexia in children does not allow concrete conclusions to be drawn about the way implicit learning develops in childhood in the face of developmental dyslexia. Consequently, a case will be made for the need for more research on implicit learning in children with developmental dyslexia.

#### 4.3.1 Research in adults with developmental dyslexia

Kelly and colleagues (2002) were the first to study implicit learning in dyslexic adult populations putting under test the automatization deficit hypothesis Nicolson and Fawcett (1990) propose (see section 2.4.1). They utilized the SRT paradigm on the basis of cerebellar activity mediating performance in SRT tasks (see section 3.4.1 & 3.5). Under a single task condition of a visuo-motor SRT task, they found that participants with dyslexia showed a similar degree of learning compared to non-dyslexic peers but had lower reaction times. Although, dyslexic participants were slower overall, the authors suggested that this does not necessarily imply an automatic sequential deficit; this delay in the response times of the dyslexic participants could be explained by other confounding factors now that there is no dual-task condition. For example, it may reflect the use of verbal strategies that the task itself encourages that are not experimentally detected. Alternatively, it may suggest poor mappings between the stimuli and their motor response or problems with focusing attention (Wimmer, Mayringer & Raberger, 1999; Kelly *et al.*, 2002).

However, Stoodley *et al*.'s (2006) finding that dyslexic adults can create good stimulus-response mappings for random sequences (similar reaction times to that of controls) but not for structured sequences (slower reaction times compared to controls' reaction times) partially contradict Kelly et *al*.'s (2002) suggestions. Stoodley *et al*. (2006) suggest that slow reaction times are indicators of an implicit motor learning deficit. They stress though, that the delay in reaction times of the dyslexic group could also be due to the high cognitive load the task imposes; it could hinder automatic skill acquisition and result in poor reading. In line with the previous studies, they credit the cerebellum as the main neural substrate; but leave open the possibility of other brain structures also being involved.

Waber et *al.*'s (2003) proposal, that neither a sequencing deficit nor the participants' performance in the SRTT can be safely used as direct indicators of reading difficulties *per se*, is reflected in Howard and collaborators (2006) study. However, Howard *et al*. (2006) shift attention to the stimuli of the task itself. They argue that previous research used stimuli with a simple sequential structure that were not probably sensitive enough to detect sequential problems. For that reason, they employed two SRT tasks that differed in sequential complexity and for which performance relies in different brain structures. First, participants were given a higher-order sequence learning task (i.e. a task that requires the integration of at least three elements). Second, participants' performance was measured on a simple spatial context cuing task (SCCT), in which "the global configuration of a display cues the location of a search target" (Howard *et al.*, 2006, p. 2). Dyslexic participants showed lower performance (i.e. slower reaction times) in the implicit higher-order learning task compared to their non-dyslexic controls but demonstrated superior performance (i.e. faster reaction times) to controls in the simple spatial cued task.

Similar to Kelly *et al*. (2002) the main thrust for explaining their findings comes from assumptions about the different brain systems involved in the two implicit learning tasks: The higher-order sequential task is thought to call on fronto-striatal-cerebellar neural substrates (e.g. Menghini et al., 2006) whereas the spatial cued task is thought to involve the medial temporal lobe which is found to be impaired in amnesic patients (e.g. Manns & Squire, 2001) and patients with elderly cognitive mild impairment (Negash *et al.*, 2004 cited in Howard *et al*., 2006). The double dissociation in the task performance of the dyslexic participants (i.e. poorer performance in the higher-order task and superior in the spatial cued task compared to the non-dyslexic group), led Howard *et al*. (2006) to propose that adults with developmental dyslexia do not suffer from a general implicit learning deficit but rather from a specific deficit in processing implicit higher-order sequential information.

Howard *et al*.'s (2006) findings are in accord with Stoodley *et al*.'s (2006) and Sperling *et al*.'s (2004) findings. Sperling *et al.* (2004) found a deficit in implicit categorical learning and intact explicit categorical learning in poor readers (including readers with developmental dyslexia). The authors in all three studies argue in favor of an implicit learning deficit that affects the application of implicit rules (Howard *et al*., 2006; Sperling *et al*., 2004) or the automatic acquisition of new complex skills and which, in combination with a phonological deficit could explain the dyslexic adults' inability to achieve fluent reading. Taken together, the findings from the aforementioned studies indicate that the implicit learning problems found in dyslexic populations could be narrowed down to a sequence-processing deficit. The failure dyslexic participants show in tasks of increased sequence complexity irrespectively of a motor or a non-motor involvement draws attention to the implicit nature itself of the tasks in use.

Very recently, Bennett *et al*.'s (2008) study comes as a support to the possibility that the implicit sequence learning deficit previously found in adult dyslexics is not confined to an implicit motor deficit but that it is somewhat related to the increased complexity of the implicit task. Bennett *et al*. (2008) examined implicit learning performance in the absence of motor sequencing using a variation of the alternating serial task that Howard *et al*. (2006) used; the triplet frequency learning task (TRIP). They also used the same SCCT to that in Howard *et al*.'s (2006) study. Additionally, the researchers administered real-word and pseudo-word tests to explore potential correlations between performance in the two implicit learning tasks and measures of readings.

The results from the TRIP task are very interesting. Although there were no group differences in learning, there was a positive correlation between TRIP accuracy and pseudo-word reading: poor pseudo-word scores were positively correlated with lower TRIP performance. The results from the SCCT are in accord with the Howard *et al*.'s (2006) study: dyslexic readers show similar performance to non-dyslexic readers and there were no significant correlations with real-word or pseudo-word tasks. Overall, the results show that dyslexic readers are spared in implicit spatial learning as measured by the SCCT but impaired in implicit sequence learning even in absence of motor sequence learning (TRIP).

This pattern of results suggests that (a) adults with dyslexia may face perceptual sequence-learning problems (e.g. fixation to targets or eye-movement problems) due to the requirements of the TRIP task (i.e. to retain perceptual traces across three elements, binding them into a triplet and compare all triplets across trials); (b) implicit learning deficits in dyslexic readers are not confined to motor components and; (c) implicit learning positively correlates with reading ability and leaves open the possibility implicit learning deficits being specific to reading impaired populations. The lack of group differences that contradicts previous findings (Howard *et al*., 2006) may be due to fact that TRIP has more high-frequency triplets compared to Howard et al.'s (2006) task and thus, could be considered easier to learn (Bennett *et al*., 2008). This adds weight to the possibility that when the difficulty of the inbuilt structure of the implicit task is increased, it is more likely for the dyslexic participants to fail.

Earlier, Russeler and collaborators (2006) compared dyslexic participants' performance on both a SRTT and an AGL task. They based their task selection on the assumption (similar to Howard *et al*., 2006) that different implicit learning paradigms are mediated by different brain systems. They anticipated that the degree of cerebellar involvement would result in impaired performance for the dyslexic participants in the SRTT but not in the AGL task. The dyslexic group performed equally well to the non-dyslexic group in both tasks leading the authors to conclude that adults with developmental dyslexia have intact overall implicit learning abilities. However, there are methodological limitations that compromise Russeler *et al*.'s (2006) conclusions. Firstly, the main assumption on which they based their design (i.e. the different brain areas activated during performance in AGL and SRT tasks) is questioned by recent fMRI studies (e.g. Lieberman *et al*., 2004) implicating the cerebellum in both AGL and SRTT. Secondly, the authors adopt a short AGL training session and they do not control experimentally over substring dependencies; the learning effects on particular item levels were not explored even though dyslexic participants had a low classification performance.

Pothos and Kirk (2004) explored implicit learning in adults with developmental dyslexia using two variants of the AGL paradigm. The stimuli were shapes that were either introduced in a sequential format (an analogy of reading) or in an embedded format (an analogy of the face). Dyslexic participants showed the same grammaticality performance in both types of stimuli whereas the non-dyslexic participants had a lower performance in the sequential task compared to the embedded task. The authors claim that dyslexic participants were not able to processes the stimuli individually because of possible co-existing attentional deficits (Facoetti *et al*., 2000) (see Chapter 2, section 4.1) that hinder their ability to process the constituent elements of a particular stimulus or to ignore its irrelevant features (Sperling *et al*., 2004). They suggest that there is an interaction between implicit and explicit processes in such a way that any potential deficits in either process may compromise learning.

Summarizing, the research data from adult populations suggest that typically developed adults have fully functioning implicit learning abilities while adults with developmental dyslexia have a specific impairment in higher-order implicit learning. This implicit learning deficit inhibits adults with developmental dyslexia from copying effectively with highly complex sequential information (Howard *et al*., 2006) in spite of intact implicit learning abilities for simple learning situations (Russeler *et al*., 2006). The research data in younger populations is even more limited; a comprehensive review is presented in the following section.

### 4.3.2 Research in children with developmental dyslexia

There are only five studies examining implicit learning in children with developmental dyslexia (Roodenrys & Dunn, 2007; Stoodley *et al*., 2008; Vicari *et al*., 2005; Vicari *et al*., 2003; Waber *et al*., 2003). Following the rationale of adult studies, the studies on children utilize the SRTT paradigm based on claims about the degree of cerebellar activation during performance and its relationship with developmental dyslexia theory.

In their first study, Vicari *et al*. (2003) used a variant SRTT, specifically a visuo-motor task of sequences of colors (implicit learning task) and a test of declarative memory (explicit learning task). They found that children with developmental dyslexia had slower reaction times in the implicit learning task but not in the explicit learning task. These results led them to conclude that children with developmental dyslexia face an implicit sequential deficit. To explore whether this deficit is specific or more pervasive in nature, Vicari *et al*. (2005) examined children's performance in different types of implicit learning tasks; a classical SRTT and a mirror drawing test (MDT) that involved different cognitive abilities.

In the case of the SRTT, the two groups of children had similar reaction times at the beginning of the task but only children with developmental dyslexia were delayed in the proceeding sessions. This led the authors to exclude motor deficits as a viable account for dyslexic children's poor performance. Instead, taking into consideration the similar pattern observed in the MDT, Vicari *et al*. (2005) concluded that there might be a general implicit sequential deficit in dyslexia that does not depend on the task material or the motor component. Because developmental dyslexia has been linked to cerebellar deficits (Chapter 2, section 4.1) and in turn, implicit sequential learning with cerebellar and striatal brain structures (Chapter 3, section 5) the authors credit the cerebellum for the pattern of their results.

Roodenrys and Dunn (2007) suggest that Vicari *et al*.'s (2003, 2005) claim for an implicit sequential deficit becomes weak when more 'sensitive' criteria are used to define implicit learning (i.e. the information and sensitivity criteria, Shanks, 1994), and when speed of stimuli presentation is considered. The view that short stimulus intervals facilitate unaware learning (Clark & Squire, 1998 cited in Roodenrys & Dunn, 2007) could compromise the validity of Vicari *et al*. (2005) interpretations, as they used longer stimulus intervals. Moreover, Roodenrys and Dunn (2008) exclude the possibility of a general cognitive deficit because according to their view MDT does not fulfill the criteria of an implicit learning task and thus no concrete conclusions can be safely made. Alternatively, Howard *et al*. (2006) claim that the tasks Vicari *et al*. (2005) used engage the same brain structures; this explains Vicari *et al*. (2005) results.

Roodenrys & Dunn (2008) tried to control for stimulus intervals effects and found no qualitative differences in performance between the dyslexic and non-dyslexic groups of children; but noted that the dyslexic group was slower. Although their findings are in line with Kelly *et al*.'s (2002) results in adults, the simplicity of their task allowed the elicitation of partially explicit strategies: priming based on fragment familiarity largely drove judgments. In other words, in their task good performance could be the result of learning simple associations between the training and the testing stimuli (e.g. McClelland & Rumelhart, 1985). Indirectly, this provides support for Howard *et al*.'s (2006) claim that simple implicit learning tasks might mask sequential deficits in the sense that while basic implicit learning abilities remain intact in the face of developmental dyslexia, more sophisticated implicit learning abilities could be impaired.

Waber and collaborators' (2003) findings are in support of Kelly's *et al*.'s (2000) suggestion that individuals with developmental dyslexia have intact implicit learning abilities. Investigating a sample of children with heterogeneous literacy and cognitive profiles, they found that the delay in response time in the SRTT was not directly related to reading but primarily to measures such as cognitive ability and attention. Waber *et al*. (2003) argue that there is no obvious connection between SRTT and reading because the SRTT is a non-linguistic task and at the same time calls for a motor response. However, participants' difficulty during performance (in terms of response time and accuracy) could indirectly influence reading in terms of fluency. In more complex and rich learning situations (such as in fluent reading performance) problems in basic information processing could hinder fundamental processes that could lead in turn, to a compromised academic performance (Waber *et al*., 2003). However, given the sample in Waber *et al*.'s study was so heterogeneous, it is difficult to incorporate those findings in the developmental dyslexia context.

Recently, Stoodley and collaborators (2008) examined implicit motor learning using a child-tailored SRT[5] task in three different groups of children, namely non-dyslexic readers, dyslexic readers and garden-variety poor readers. Although there was no difference between the groups in terms of performance accuracy, the dyslexic group

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[5] The task was longer in terms of trials; but this does not seem to affect children's performance verified by Vicari *et al*. (2003, 2005) studies that used longer number of trials.

had much slower reaction times compared to the rest of the groups. The authors claim that children with developmental dyslexia have poor implicit motor learning, which can explain their arduous learning. Implicit motor learning is associated with the cerebellum (e.g. Nicolson & Fawcett, 1999) and the neighboring neural circuits (Laycock *et al*., 2008; Nicolson & Fawcett, 2007); abnormalities in the cerebellum and/or in the adjacent neural connections are held responsible for problems in the processing and the integration of information and hence, for difficulties in automatization of skill learning.

Interestingly, in Stoodley *et al.*'s (2008) study reaction times correlated with the size of the discrepancy between the literacy and cognitive profiles of the children: the children that had poor literacy profiles but discrepant IQ (i.e. children with developmental dyslexia) had also poor implicit motor learning performance. This finding directly contradicts Waber *et al*.'s (2003) findings, suggesting that children who share a similar literacy profile may face problems in different literacy acquisition mechanisms (Stoodley *et al*., 2008). The "flat learning curve" (Stoodley *et al*., 2008, p. 181) of the dyslexia group as opposed to the good learning rate of the garden-variety group suggests that implicit learning problems may be specific to children with developmental dyslexia. This possibility is subject to future research.

## 4.4 Summary: The function of implicit learning abilities in developmental dyslexia

To date, implicit learning is highly functional in typical populations as behavioral and neuroanatomical data reported in Chapter 3 have shown. The findings from typical populations suggest that implicit learning is not a unitary phenomenon; there are different implicit learning abilities (e.g. implicit motor learning, implicit higher-order learning and implicit spatial learning) that are measured via different implicit learning tasks. Consequently, those different implicit learning abilities may interact with different explicit abilities. This interaction results to developmental variance of implicit learning contradicting this way the prevailing view of implicit learning that is being developmentally invariant (Reber, 1989).

So far, studies of implicit learning and developmental dyslexia have resulted in a contradiction. The corpus of studied presented earlier provides different accounts for the way implicit learning abilities function in developmental dyslexia: some studies suggest a specific implicit learning deficit (Howard *et al*., 2006; Sperling *et al*., 2004; Stoodley *et al*., 2006) whereas other studies are in support of a generalized implicit learning deficit (Vicari *et. al,* 2005; Vicari *et al.*, 2003). A third group of studies reports intact implicit processes in dyslexic populations (Kelly *et al*., 2002; Roodenrys & Dunn, 2007; Russeler *et al*., 2006). The controversial and contradictory findings of the studies could in part be the result of sample selection criteria (Roodenrys & Dunn, 2007) or the different experimental procedures used (e.g. Vicari *et al*., 2003).

Nevertheless, the thesis makes some tentative conclusions with regard to the way implicit learning seems to function in developmental dyslexia: (a) there is strong evidence that while basic implicit learning abilities (e.g. spatial implicit learning) remain robust other more sophisticated abilities (e.g. implicit higher-order learning) are affected; (b) implicit learning deficits seems to be related to the inherent sequential complexity of the tasks; the higher the complexity the lower the task performance; (c) implicit learning deficits are not related to IQ or age and; (d) implicit learning deficits can still be present even if explicit learning abilities are intact.

## 4.5 Discussion

Given that the limited research in typical children and children with developmental dyslexia does not fully support the claim of developmental invariance of all implicit learning abilities, new research should focus on children who share a different developmental profile. Further research on the implicit learning abilities of children with developmental dyslexia could confirm or refute the notion of developmental variance in implicit learning abilities.

All the paradigms tapping into implicit learning abilities are potentially workable with older children but the vast majority of studies on implicit learning in children with developmental dyslexia have been carried out using the SRTT paradigm (e.g. Stoodley *et al.*, 2006; Vicari *et al.*, 2003). Therefore, the thesis argues that implicit learning abilities should be further studied in children with developmental dyslexia using alternative implicit learning paradigms. Using alternative implicit learning paradigms that provide learning situations of a different complexity at the cognitive level is a fruitful way of investigating implicit learning in children with developmental dyslexia.

Artificial grammar learning (AGL) is proposed as the paradigm of choice for the present thesis for two main reasons: First, it differs in some of its aspects from the rest of the implicit learning paradigms (see Chapter 3, section 4.2) so, its use will provide us with further information on different aspects of implicit learning abilities. AGL is thought to tap into different processes from those involved in SRTT (and its variations such as simple cued recognition task). Simple cued recognition tasks involve simple figural goodness of visual priming stimuli (Schacter, Chiu, & Ochsner, 1993) whereas the complexity of AGL tasks requires more abstract and conceptual representations as the stimuli are so similar in their surface features that some rule knowledge seems mandatory to cope with the demands of the tasks (Dienes, 1992). Most importantly, the SRTTs have received criticism (see Chapter 3, section 4.1) for inducing explicit learning. SRTT are thought to involve more explicit processes compared to AGL where findings support that learning is largely implicit.

Second, AGL is a widely used experimental paradigm in adult research (Reber, 1993, 1989, 1967). However, it has proven flexible enough for work for infants (Gomez & Gerken, 1998; Marcus *et al*., 1999) and for young populations (children as young as nine years old) both typically developing and with various developmental disorders such as autism (Don, Schellenberg, Reber, DiGirolamo, & Wang, 2003). Thus, it is a suitable paradigm to explore implicit learning in children with developmental dyslexia.

In the following three chapters, the thesis presents a set of five experiments using the AGL paradigm. The experiments contrast the performance of children with developmental dyslexia to the performance of typically developing children. The general aim of the studies is dual: To explore the possibility of developmental variance in implicit learning abilities in childhood and to examine the way in which potential deficits in implicit learning mechanisms relate to developmental dyslexia theory.

# CHAPTER 5

# STUDY 1: EXPLORING IMPLICIT LEARNING ABILITIES IN PRIMARY SCHOOL CHILDREN WITH AND WITHOUT DEVELOPMENTAL DYSLEXIA: THE CASE OF ARTIFICIAL GRAMMAR LEARNING (AGL)[6].

## 5.1 Aims of this chapter

This chapter presents the first study of the thesis. Two experiments are conducted and presented under separate headings: Experiment 1 and Experiment 2. The experiments employ the artificial grammar learning (AGL) paradigm that has been extensively used to study implicit learning performance in typically developing adults (e.g. Dulany, Carlson & Dewey, 1984; Pothos & Bailey, 2000) and in adults with amnesia (Knowlton & Squire, 1992, 1996). However, the same paradigm has been used only in studies in adults with developmental dyslexia (Pothos & Kirk, 2004; Russeler et. al, 2007). Here, for the first time, the AGL paradigm is applied to children with developmental dyslexia. The chapter examines whether more complex implicit learning abilities (as these tested in AGL) are impaired in children with developmental dyslexia and therefore, are subject to developmental differences between typically developing children and children with developmental dyslexia.

Earlier findings on implicit learning abilities in children with developmental dyslexia focused on implicit sequential learning using the SRTT paradigm (see

[6] The data from this study have been published in *Annals of Dyslexia* (see Appendix I)

Chapter 4). The ability to perform well on SRTT encompasses both motoric and cognitive demands, namely the ability to respond quickly to the presented stimuli and to be sensitive in first-order dependencies (i.e. one preceding item in the sequence correctly predicts a following item, Gomez, 1997). AGL on the other hand, does not have any motor engagement and performance is thought to rely primarily on hierarchical learning, which is the abstraction of higher-order dependencies (i.e. one preceding item correctly predicts multiple (at least two) following items). The abstraction of knowledge, either specific (e.g. Perruchet & Pacteau, 1991) or rule-like (e.g. Dulany *et al*., 1984; Reber, 1967), is perceived as being a prerequisite for good performance (Sallas, Mathews, Lane, & Sun, 2007).

## 5.2 Introduction

To date, research in developmental dyslexia has mainly focused on specific deficits in explicit learning that are associated with the condition (presented in Chapter 1). Central to the study of these specific conscious experiences is the claim of one core etiology that could explain the wide spectrum of developmental dyslexic phenomena. However, findings have not supported this claim satisfactorily. The inability of the main theories to account for all the behavioral markers of developmental dyslexia on one hand, and the specificity of the claims they make, leaves room for the study of more global non-linguistic abilities (e.g. Nicolson & Fawcett, 1990) that could be extended to linguistic material.

The predominant explanation for developmental dyslexia is a deficit in phonological processes (Snowling, 2000). Yet the finding that reading problems tend to persist even when good explicit linguistic abilities can be established (as illustrated in Chapter 2), led a line of research into broader non-linguistic perceptual/motor abilities, for example, automatization in skill learning (e.g. Nicolson & Fawcett, 1990) and into other types of learning such as implicit learning. Developmental dyslexia, being primarily a learning difficulty, should be further studied in the learning literature framework. The thesis argues that implicit learning is a suitable and advantageous paradigm to use. It will shed light on fundamental (and possibly innate) non-linguistic learning abilities in childhood and on how the development of these abilities affects reading in developmental dyslexia.

As discussed earlier in Chapter 3, the study of implicit learning in typically developing adults tends to show relative stability of the implicit learning processes throughout adulthood. The limited research on typically developing children, mainly designed to discover how age and IQ influences implicit learning, has revealed contradictory results (Thomas & Nelson, 2001; Vinter & Perruchet, 2000). The older and more intellectually advanced children seem to perform better compared to younger and less intellectually advanced children (Thomas & Nelson, 2001), but this finding is not consistent across studies (Vinter & Perruchet, 2000). In the case of atypical populations (i.e. people with developmental dyslexia) the findings are also inconsistent.

Chapter 4 presented a comprehensive review of the research work on populations with developmental dyslexia and reached some tentative conclusions about the way implicit learning abilities appear to function in the presence of developmental dyslexia. The review showed that (a) the noted implicit learning deficits in developmental dyslexia tend to be specific in nature (pointing to the possibility different implicit learning tasks tapping into different implicit learning abilities); (b) implicit learning deficits in developmental dyslexia are not related to general IQ; but they are related to (c) increased complexity of the sequential structure of the implicit learning environment and; (d) implicit learning deficits are present even when explicit learning is found intact.

However, there are a number of limitations in the corpus of studies conducted in developmental dyslexic populations that highlight the need for additional research to obtain a clearer picture of how implicit learning operates in the face of developmental dyslexia. As outlined with more detail in Chapter 4, the number of studies in developmental dyslexia is very limited and has almost exclusively used the SRT paradigm. The majority of those studies investigated implicit learning in adult populations making indirect inferences for the robustness of implicit learning across all age groups. Moreover, none of the studies have explored developmental factors other than age that might influence implicit learning (and the resulting knowledge). Finally, none of the studies have explored more systematically the interaction between implicit and explicit learning.

Taking into consideration the limitations set out above, it is critical to study implicit learning in children with developmental dyslexia using a potentially more illuminating paradigm and to contrast their performance to that of typically developing peers. The discrepancy in the findings of implicit learning indicates that different research paradigms tap into different implicit learning processes (Bennett *et al*., 2008; Howard *et al*., 2006; Roodenrys & Dunn, 2007). Therefore, the employment of an alternative implicit learning paradigm will give an insight of different implicit learning abilities in developmental dyslexia other than those already explored by the SRT paradigm. Thus, the present study makes use of the AGL paradigm.

AGL has a number of advantages that make it highly profitable for the investigation of potential implicit learning deficits in children with and without developmental dyslexia. First, AGL has technical properties that allow the examination of different factors that may affect performance, for example, its sequence complexity can be broken down, quantified and experimentally measured. Thus, the sequential format of the AGL stimuli can account for different psychological interpretations of participants' performance depending on the focus (and/or the rationale) of the study that utilizes it. Also, by altering the nature and circumstances of presentation of the set of instructions, AGL performance can take up a more passive ('purely' implicit) or a more explicit (e.g. working memory involvement) mode. In other words, the psychological salience (nature of instructions) and the timing of presentation of the instructions (circumstances) could help existing differences in the learning rate between typical children and children with developmental dyslexia to emerge.

Second, AGL taps into different processes than those involved in SRTT (and its variations such as simple cued recognition task). Simple cued recognition tasks (see Roodenrys & Dunn, 2007), for example, involve simple figural goodness of visual priming stimuli (Schacter, Chiu, & Ochsner, 1993) that require first-order sequential learning. In contrast, the high complexity of AGL requires more abstract and conceptual representations. The stimuli are so similar in their surface features that some rule knowledge seems mandatory to cope with the demands of the task (Dienes, 1992). Thus, higher-order abstract learning takes place across the training stimuli to predict the task-relevant features of the testing stimuli (Dienes, 1992). Moreover, AGL calls on fronto-striatal-cerebellar circuits (see Chapter 3, p. 66) that are associated with developmental dyslexia (e.g. Nicolson & Fawcett, 1999) on the basis of the common links these circuits may share with reading.

Most importantly, although AGL is a widely used experimental paradigm in adult research (Reber, 1993, 1989, 1967), it has also been used successfully in infants (Gomez & Gerken, 1998; Marcus *et al*., 1999) and children as young as nine years old both typically developing and with various developmental disorders (Don, Schellenberg, Reber, DiGirolamo, & Wang, 2003). This, along with the features presented above, makes AGL a suitable paradigm for doing research with typical children and children with developmental dyslexia.

### 5.3 The present study

Study 1 explores how robust is implicit learning in typically developing children and children with developmental dyslexia using, for the first, the AGL paradigm. Developmental differences (e.g. the kind of deficits that can potentially be found in children with developmental dyslexia such as impaired perception, attention and/or memory, Fletcher *et al.,* 2000) that may exist between typical children and children with developmental dyslexia can account for a developmental effect on implicit learning. At the same time, however, the majority of complex skills in natural settings require the simultaneous use of explicit and implicit processes (Reber, 1989) and individuals with developmental dyslexia have been reported to associate deficits in both processes. Thus, it should be possible to build two different AGL experiments that can either increase or minimize the way children use a blend of implicit and explicit processes.

The experimental manipulation of the instruction set (i.e. the kind of task-relevant information participants receive and the exact time they receive this information) can affect AGL performance (Reber, 1976) by either hindering or facilitating performance (see p. 64). This, provides the means for creating two different experimental scenarios and raises the question of whether the circumstances (time) and the nature (psychological salience) of the instructions will affect implicit learning performance differentially for typical and developmental dyslexic children. This way, explicit influences on implicit learning will be studied more thoroughly.

Thus, *Experiment 1: Implicit instructions*, is a typical application of an AGL task where no explicit instructions (see Appendix F.4) are given at the beginning of the training phase but there is extensive passive exposure to sequential stimuli (see pp. 47-49, first criterion for implicit learning). This type of task primarily induces implicit learning (see Chapter 3, sections 3 & 4.2), which is reflected in above chance overall performance. The main research question that Experiment 1 explores is whether children with developmental dyslexia will show the same level of performance in this highly complex task compared to typically developing children, as research in adults with developmental dyslexia has indicated (Pothos & Kirk, 2004; Russeler *et al.,* 2006).

In *Experiment 2: Explicit instructions*, more explicit information about the rule-governed nature of the stimuli is given at the beginning of the training phase. Children are prompt to memorize as many items as possible and to try to discover the underlying rules. Experiment 2 encourages the use of explicit learning abilities and thus, allows a preliminary investigation of implicit/explicit influences in AGL. More specifically, the experiment explores whether the introduction of explicit information prior to AGL training phase (see Reber, 1976) will induce explicit learning processes, which may interfere with implicit learning and consequently, affect AGL performance.

### 5.4 Experiment 1: 'Implicit Instructions'

Experiment 1 adopts a typical AGL experimental protocol in terms of both the nature and the timing of instructions throughout the task (see Method section below). The instruction set that children receive in the beginning of the training phase is implicit in that it does not alert the children to issues with regard to the grammaticality of the training stimuli; children are just asked to observe the stimuli (see Appendix F.4). No other information regarding the form, the length and the structured nature (i.e. rule-governed sequences) of the stimuli is provided. Therefore, it is assumed that the kind of learning taking place will be primarily implicit so, failure in the task will indicate potential implicit learning deficits.

### 5.4.1 Method

#### 5.4.1.1 Participants

In Experiment 1, the total number of primary school children tested was 32 (16 boys and 16 girls). All 32 children were recruited from seven private and state primary schools covering a wide range of socio-economic catchment areas in Edinburgh City Council (see Appendix B). Informed consent was sought after all safeguards (see Appendix D) and stakeholders and the ethical guidelines were carefully followed to meet high research standards (see Appendix A).

The participating children were divided into two groups. Sixteen children out of the 32 formed the 'dyslexia group' on the basis of formal diagnosis of developmental dyslexia. No such condition was reported for the remaining 16 children that comprised the 'typically developing group'. Typically developing children and children with developmental dyslexia were selected from the same classrooms and were matched according to their chronological age with mean age 10y 7m (SD= 0. 98) and biological sex; for every boy and every girl with developmental dyslexia a matching typically developing boy and girl were included. This selection procedure aimed to counterbalance socio-economic level and teaching influences amongst the sample of children.

For the purpose of Study 1, the attribution of dyslexia in the sample was established based on standard diagnosis from authorized state educational psychologists. There is a typical diagnostic procedure followed by each appointed educational psychologist that applies for all state/private Scottish schools. Children are given a standardized battery of dyslexia screening tests (Nelson's Dyslexia Screener), reading and spelling tests (Graded Word Reading Test and Single Word Spelling Test) and other cognitive measures (such as British Picture Vocabulary Scale and Ravens matrices). A discrepancy criterion was applied to reading ability in relation to IQ. The cognitive measures differed sometimes between the schools so, it wasn't possible to display coherent cognitive profile for all children. However, all children had IQ with the normal range. Children are also subject to overall ongoing profile screening from their teachers looking at other aspects of the curriculum in order to monitor their reading and spelling abilities (see Table 5.1) as well as their verbal and non-verbal intelligence. The teachers screened out any participants who exhibited any behavioral indicators of comorbid conditions such as attention hyperactivity disorder.

**Table 5.1:** Summary of reading and spelling performance

| Dyslexia group | Reading (5-14)[a] | Spelling age |
|---|---|---|
| Child 1 | C (D) | 7years |
| Child 2 | B (C) | 7years |
| Child 3 | B (C) | 6years 8months |
| Child 4 | C (D) | 6years 7months |
| Child 5 | C (D) | 6years 9months |
| Child 6 | B (C) | 6years 7months |
| Child 7 | B (D) | 6years 9months |
| Child 8 | B (C) | 6years 9months |
| Child 9 | C (C)* | 7years 1month |
| Child 10 | B (C) | 7years |
| Child 11 | B (C) | 7years 2months |
| Child 12 | B (C) | 7years |
| Child 13 | A (B) | 6years 5months |
| Child 14 | B (C) | 6years 7months |
| Child 15 | B (D) | 7years 1month |
| Child 16 | B (C) | 7years |

[a] Attainment level on national tests. The scale for primary students ranges from A (being the lowest level of achievement) to E (or above). The brackets indicate the level children should have reached according to their chronological/schooling age.

* Child's 9 reading attainment level is at expected level but spelling performance 2 years below. Note that the results of the experiment do not change even when Child 9 is excluded.

No such condition or any problems with reading or spelling were reported for the typically developing group. All the children who formed ‘the typically developing group’ were students who met the national standards for reading and spelling performance (see Table 5.2). It was assumed that all typical children had an IQ within the normal range because there weren’t any reported diagnoses or problems with general intelligence. Children had been recently given a battery of IQ tests and those included were referred by their teachers as having IQ performance within the normal range. Because the cognitive measures that are administered differ from one school to the other, it was not possible to display a coherent cognitive profile for all children. However, all the children that were included in the study had basic cognitive abilities within the normal range. Furthermore, following other studies in developmental dyslexia and implicit learning that did not use any additional measures such as literacy batteries (see Vicari *et al.,* 2003, 2005), it was decided not to run any additional cognitive measures to establish their normality.

It has to be noted that the variability in the attainment scores as depicted in Tables 5.1 and 5.2 relates to children’s chronological age: there are different set levels for different ages. Therefore, although the overall chronological band is narrow, one chronological year difference between any two children would set different attainment goals for each.

**Table 5.2**: Summary of reading and spelling performance

| Typically developing group | Reading (5-14)[a] | Writing (5-14)[a] |
|---|---|---|
| Child 1 | D(D) | D(D) |
| Child 2 | C(C) | C(C) |
| Child 3 | C(C) | C(C) |
| Child 4 | D(D) | D(D) |
| Child 5 | D(D) | D(D) |
| Child 6 | C(C) | C(C) |
| Child 7 | D(D) | D(D) |
| Child 8 | C(C) | C(C) |
| Child 9 | D(D) | D(D) |
| Child 10 | C(C) | C(C) |
| Child 11 | C(C) | C(C) |
| Child 12 | C(C) | C(C) |
| Child 13 | B(B)* | B(B)* |
| Child 14 | C(C) | C(C) |
| Child 15 | D(D) | D(D) |
| Child 16 | C(C) | C(C) |

[a]Attainment level on national tests. * Child 13 is the youngest that is why the attainment level differs from the rest.

#### 5.4.1.2 Materials
#### 5.4.1.2.1 The artificial grammar learning (AGL) task

The AGL task was developed from the Knowlton and Squire (1996) Experiment Grammar 1 (see Figure 5.1). Following the permissible paths of the grammar, 23 items were created. The training stimulus set (see Appendix F.1) consisted of a total number of 69 items (i.e. 23 X 3) that were composed of between two and six elements. The testing stimulus set (see Appendix F.1) had 32 novel items, which had an equal number of grammatical (G) and non-grammatical (NG) items. The NG items were constructed by introducing one error in each of the novel G items that were created following the grammar's (*IN* and *OUT)* arrows.

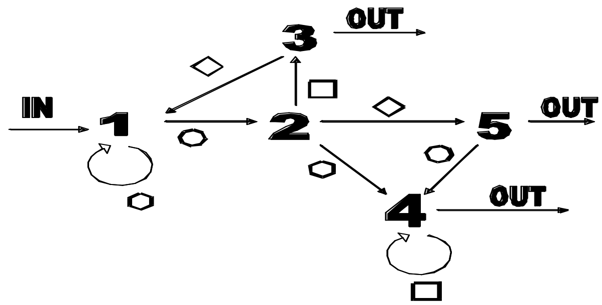


**Figure 5.1** The Grammar used as developed from Knowlton and Squire (1996) Experimental Grammar 1. The letters were replaced from shapes as follows: X= hexagon, V=circle, T= diamond and J= square.

Depending on the number of bigrams and trigrams each G and NG item contains, its associative chunk strength differs respectively. Associative chunk strength for each test item is the mean number that is calculated by dividing the total number of bigrams and trigrams it consists of, with the number of times these bigrams and trigrams had appeared during the training phase (e.g. XXVTV contains the following bigrams: XX, XV, VT, TV and trigrams: XXV, XVT, VTV; its associative strength is: 39+45+18+21+24+12+6=165; 165/7= 23.6). Experiment 1 used testing G and NG items that were matched for chunk strength; the testing stimulus set had an equal number of *high* chunk strength (HCS) and *low* chunk strength (LCS) items (see Appendix F.3). The experimental materials were balanced for chunk strength so that explicit influences during the task could be experimentally controlled for (see Chapter 3 on implicit knowledge representation). This way the effect of explicit factors relating to similarity and fragments (see section 3.6) can be controlled and explicit influences can be attributed/calculated independently accounting for different interpretations of the two groups' performance.

The original training and testing stimuli (i.e. sequences of letters) that were created (and calculated in terms of associative strength) were then replaced with sequences of simple geometrical shapes (circle, square, diamond and hexagon) as follows: X = hexagon, V = circle, T = diamond and J = square (Pothos & Kirk, 2004) (see Appendix F.2). An example of an alternative grammatical sequence is shown in figure 2 below. The choice to replace the original letters with shapes was made to eliminate the possibility children with developmental being 'intimidated' by the sight of letters; thus, minimizing the amount of stress during task performance. It has to be noted at this point that, at least in adult research, there is evidence that performance with such stimuli is not different compared to performance with standard AGL stimuli (Pothos, Chater & Ziori, 2006; see also, Pothos & Kirk, 2004).

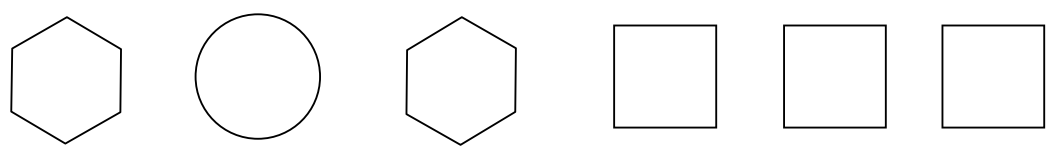

**Figure 5.2** An example of a grammatical (G) sequence as developed from Knowlton and Squire (1996; Exp.1) grammar.

The 32 alternative testing stimuli were further divided into two versions that are referred as 'Stimuli order A' and 'Stimuli order B'. The 'Stimuli order B' were the reverse order of trials of Stimuli A. Within each group, half of the children (8) were given stimulus order A and the rest of the children were given stimulus order B. It was decided to create two stimulus orders as an additional way of 'blocking' the stimuli; to hinder explicit learning influences related to shape probability or shape repetition (Dulany *et al*., 1984, 1985).

#### 5.4.1.3 Preparatory phase

Prior to any experimental session, the experimenter met with the learning support teacher (or with the Head teacher) to organize (a) a visit plan that would cause the least inconvenience to the children themselves and their school routine and (b) an adequate working place for the experimental sessions to take place. The working space had at least one table with the computer on it and two chairs side by side about 30- 40 centimeters apart: one in front of the computer for the child to seat in and one on the right hand side for the researcher to be seated.

All the children were informed in advance by their learning support teachers or their regular teachers about the project but not in full detail to avoid biases that could influence their performance on the task. They were also informed that they would work with the researcher on an individual basis and only for once. In most of the schools, the experimenter met with the children before any experiment takes place, to familiarize with her presence in the school.

#### 5.4.1.4 Procedure

The researcher welcomed the child and asked him/her to take a seat in front of the computer. A brief conversation took place before the introduction of the task to create a friendly and relaxed atmosphere that would minimize the level of performance anxiety. In some cases, it was obvious that the child was nervous about what was about to happen so, the researcher felt that it was mandatory to find ways of relaxing the child in question. The child was told that she/he could opt out at any time during the task (see Appendix A). Then, the researcher described in a few words what was about to happen: She informed the child that she/he would be given a computer task with geometrical shapes and that she/he should follow carefully the instructions.

The AGL task was held on a portable ACER computer screen. Before the beginning of the training phase, the child was introduced with a set of instructions on the computer screen (see Appendix F.4). The instructions informed the child that (a) the experiment was divided in two parts; (b) a series of items that are made up of geometric shapes would follow; (c) she/he had to observe the stimuli very carefully; and; (d) she/he could only ask any questions now and not while observing the geometric shapes. The child was asked to take time to read the instructions. Then the researcher read them again aloud, answered any questions[2] the child had in such a way that would not affect performance and proceeded to the training phase. The training stimuli were presented on the computer screen; one item at a time and in a consecutive order. Each item remained on screen for 5 seconds until the child was exposed to a total of 69 training items. This phase lasted 6 minutes during which the child was not asked to make any response with regard to the stimuli.

When the exposure to the training stimuli was over, the child was given a new set of written instructions; the ‘explicit’ instructions (see Appendix F.4.b). This time, the

[2] A number of children didn’t know the word ‘geometric’ so the researcher explained that they were “shapes such as circle and square”.

instructions informed the child that the second phase of the experiment (i.e. the testing phase) would begin. Also, the instructions told the child that (a) the sequences of shapes she/he had just seen were following a complex set of rules (e.g. only certain shapes can follow other shapes); (b) she/he would see a new set of items and had to decide whether the news items follow the rules or not; (c) she/he should say YES if the item followed the rules and NO if the item did not follow the rules; (d) if he/she was not sure what these rules were, she/he could guess and; (e) the items would remain on screen until the she/he provided an answer, however, she/he was encouraged to answer as quickly as possible. The child was asked to take time to read the instructions. Then the researcher read them again aloud and prompted the child anew to ask any questions before they proceeded. Again, the researcher answered questions in a neutral way to avoid biases towards task-relevant information that could affect the child's performance during the testing phase.

The child was shown 32 items in total. Each item was presented individually. Each item remained on the screen until the child made a grammaticality judgment (i.e. to decide whether the new item followed the same rules with the old (training) items). A new item was introduced on the screen only after the child gave a YES or a NO answer to the preceding item. The researcher recorded the child's answer on paper format. Once the child had completed the testing phase (i.e. made a grammaticality judgment for all 32 items of the testing phase) she/he was given a post-experimental interview. The child was asked if she/he noticed a pattern and if she/he used this pattern to make grammaticality judgments. Most of the children (30) replied that they made guesses whereas only two (one typically developing and one with developmental dyslexia) claimed that they used some kind of strategy. They said that they had noticed that specific shapes were following other specific shapes but could not give an example. Neither of the children could describe verbally the strategy they claimed to have used to make their judgments.

#### 5.4.1.5 Design

The Experiment is a 2 (group: children with dyslexia, typically developing children) X 2 (grammaticality: grammatical (G), non-grammatical (NG)) X 2 (chunk strength: high chunk strength (HCS), low chunk strength (LCS)) mixed design. Classification performance is measured on the two dependent material variables (i.e. grammaticality and associative strength). First, the total number of G and NG items correctly identified as G and NG respectively (Grammaticality) is calculated. Second, the total number of HCS and LCS items (Chunk strength) both G and NG is also calculated.

### 5.4.2 Results[7]

Data was analyzed in a comprehensive way following other studies on AGL (Knowlton & Squire, 1994, 1996; Pothos & Kirk, 2004; Russeler *et al.,* 2006). First, one sample independent *t*–tests for each group of participants were employed to assess the learning that took place. The total number of correct grammaticality judgments (G and NG both HCS and LCS including Stimuli order A and Stimuli order B) was compared against chance levels. In the task, maximum performance would be 32, minimum performance 0 and chance performance 16. The *t*-test for the

[7] It has to be noted that results did not change even when children 9 and 13 from the dyslexic and control group respectively were excluded from the analysis.

typically developing group revealed that AGL performance significantly exceeded chance levels ($t_{(15)} = 5.12$, $p < 0.01$, $M = 18.94$ SD = 2.29). In contrast, the *t*-test for the dyslexia group showed that children with developmental dyslexia performed at chance levels ($t_{(15)} = 0.62$, $p > 0.05$, $M = 16.50$ SD = 3.20). AGL performance for both groups is shown in Figure 5.3 below.

The Effect size[8] was calculated ($d = 0.87$) in order to further assess the degree of significance obtained by the *t*-test for the performance of typically developing group compared to the performance of the dyslexic group. The effect size was large and thus, the learning difference between the groups was indeed significant. Cohen's *d* mitigates the small overlap in performance.

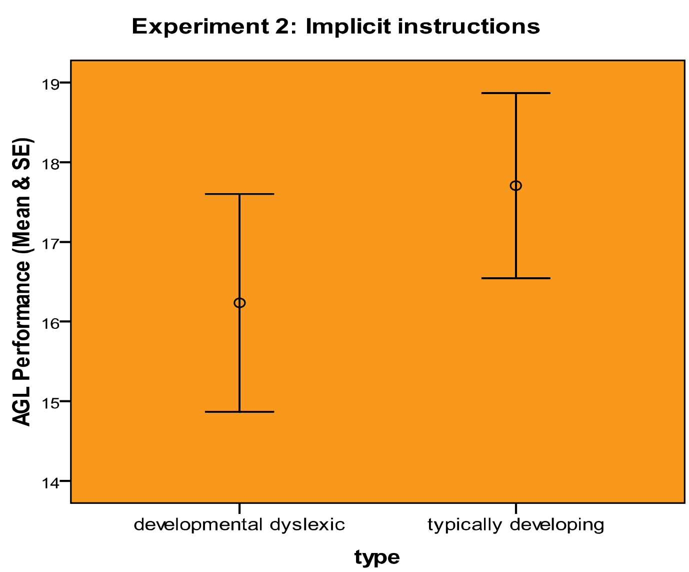


**Figure 5.3** AGL performance (Experiment 1: Implicit instructions) as expressed in terms of the standard error of the mean correct classification judgments.

[8] Effect size was calculated using SD for both groups.

To address whether the difference in the learning (as indicated from the independent *t*-tests) between the two group of children was related to substring characteristics of the stimuli (i.e. grammaticality and associative strength), an ANOVA (repeated measures) was employed, with one factor corresponding to group (dyslexic, typically developing), a second one to grammaticality (G, NG) and a third one to chunk strength (HCS, LCS). The ANOVA revealed a main effect of group ($F_{(1,30)}$ = 8.18, $p < 0.01$). There was also a main effect of grammaticality ($F_{(1,30)}$ = 5.81, $p < 0.05$) such that G items elicited more correct responses as opposed to NG items. The typically developing group outperformed the dyslexia group showing learning in terms of grammaticality. There was no main effect of chunk strength; the associative strength of the testing items to the training items did not affect classification performance for any of the groups.

There were no 2-way interactions. However, there was a marginal 3-way interaction ($F_{(1,30)}$ = 3.89 $p$ = 0.058) so, it was decided to run simple *t*-tests for each stimulus type (i.e. grammatical, non grammatical, of high chunk strength and of low chunk strength) to further examine the performance of the children across the specific substring dependencies. The *t*-tests compared children's classifications for each of the four different types of items against chance levels. *T*-tests for the typically developing group were significant for all items (G items: ($t_{(15)}$ = 4.06 $p < 0.05$ $M$ = 10.69, SD = 2.65; HCS items: $t_{(15)}$ = 2.22 $p < 0.05$ $M$ = 8.94, SD = 1.7; LCS items: $t_{(15)}$ = 5.48 $p$ = 0.000 $M$ = 10, SD = 1.46) except for NG items ($t_{(15)}$ = 0.34 $p > 0.05$ $M$ = 8.25, SD = 2.95). Typically developing children scored at above chance levels in almost all types of items; they showed evidence of learning both in terms of grammaticality and associative strength. In direct contrast, all *t*-tests for the dyslexia group were not significant: Children with developmental dyslexia scored poorer than typically developing children regardless of the type of item. Both groups' performance on the four different types of stimuli (i.e. G, NG, HCS and LCS) is depicted in figure 6.4 as the mean number of correctly identified stimuli.

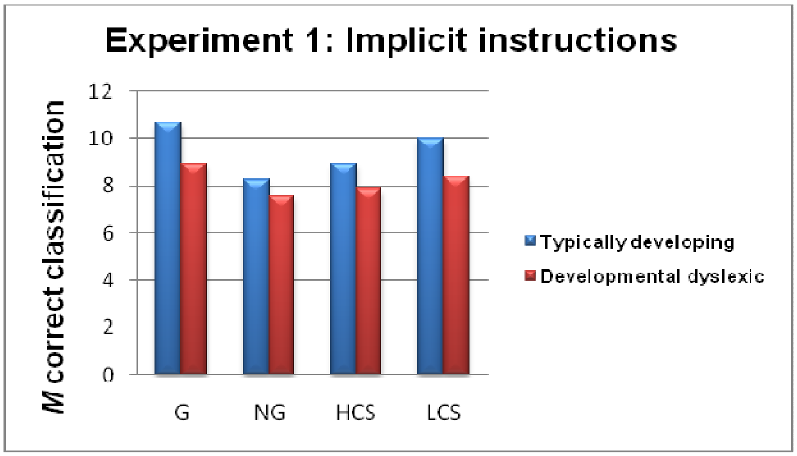


**Figure 5.4** Mean endorsement rates for each type of item separately.

Finally, to explore stimulus order effects on classification performance a two-way ANOVA was run, examining group (children with dyslexia, typically developing) X stimulus order (order A, order B). The ANOVA was not significant ($F_{(3,31)} = 0.14$, p > 0.05). Thus, stimulus order did not affect classification performance for the two groups in any interesting way.

### 5.4.3 Discussion

Experiment 1 explored whether children with developmental dyslexia will show the same performance compared to their typically developing peers in an AGL task. AGL was employed for the first time in children with developmental dyslexia. Overall, the results from the data analysis (i.e. *t*-tests and ANOVA's) showed that children with developmental dyslexia responded based on ‘gut feeling’. The lack of evidence for learning (i.e. performance at chance level) suggests that children with developmental dyslexia weren’t able to meet the demands of the task. On the contrary, typically developing children scored at above chance levels and outperformed children with developmental dyslexia (group effect). This pattern of results concurs with previous studies using typically developing children, which report similar findings (Don *et al*., 2003; Gomez & Gerken, 1998; Marcus *et al*., 1999; Meulemans *et al.,* 1998; Vinter & Perruchet, 2000). Interestingly, typically developing children outperformed children with developmental dyslexia both in terms of grammaticality and associative strength; children with developmental dyslexia failed to show learning regardless of the specific item dependencies (i.e. grammaticality or chunk strength).

Since it has been proposed that for accurate performance in AGL the acquisition of implicit rules is a prerequisite (Sallas *et al*., 2007), it is argued that children with dyslexia are impaired in implicitly abstracting the grammar rules. They face difficulties abstracting higher-order information across the stimuli and thus, fail to show implicit learning as manifested in the AGL context. This finding contradicts findings from other studies, which support intact basic implicit processes in children with developmental dyslexia (Roodenrys & Dunn, 2007); but this does not necessarily constitute a paradox. Instead, it verifies that in children with developmental dyslexia more basic implicit learning processes (e.g. first-order implicit learning as tested with a simple variation of a SRTT (Roodenrys & Dunn, 2007) or SCCT (Bennett *et al*., 2008; Howard *et al*., 2006)) remain intact whereas more sophisticated implicit learning processes (i.e. higher-order learning), on which AGL performance lies, are impaired. Thus, children with developmental dyslexia are found to be impaired in their implicit learning abilities (i.e. higher-order learning) as those tested by AGL. Moreover, the inconsistency of the present findings with findings from studies in dyslexic adults that used the AGL paradigm (see Russeler *et al*., 2006; Pothos & Kirk, 2004) suggests underlying age differences in implicit learning development in individuals with developmental dyslexia (future work could examine this systematically).

The data from Experiment 1 also contributes to the discussion over the kind of knowledge children acquire (see Chapter 3, section 6) and on the amount of explicit influences during AGL. Typically developing children showed learning of items with high associative strength (see *t*-tests for HCS and LCS items). However, there was no strong evidence (no chunk strength effect) for fragment-based influences (i.e. knowledge of bigrams and trigrams). The similarity of the novel items (i.e. testing items) to the old items (i.e. training items) cue episodic representations of the previously experienced training items (Shanks & St.Johns, 1994) enhancing the acquisition of fragment knowledge (Pothos, 2007). As discussed in Chapter 3, although bigrams account for a large amount of information children acquire during AGL (Perruchet & Pacteau, 1990, 1991), they do not account for other factors such as the sensitivity to positional higher-order dependencies (grammaticality effect). Thus, typically developing children acquired more information about the items than just bigrams. It is very likely that the acquired information is in the form of abstract rules (e.g. Reber *et al*., 1980). The increased sequential complexity of the stimuli and the incidental instructions elicited implicit abstraction mechanisms for typically developing children. But for children with developmental dyslexia this increased complexity did not allow the elicitation of similar learning mechanisms. Children with dyslexia exhibited problems coping with an environment as highly complex as the one provided by the AGL paradigm and thus, failed to show implicit learning.

To summarize, Experiment 1 results suggest that implicit higher-order learning is found impaired in children with developmental dyslexia while it is intact in typically developing children. In addition, AGL training seems to result in the formation of both abstract rule-like knowledge (Reber, 1967; Dulany *et al*., 1985) and fragment-based knowledge (Perruchet & Pacteau, 1990, 1991; Perruchet, Vinter, Pacteau & Gallego, 2002). The extensive passive exposure to training items without any prior explicit information about the relationship between the stimuli facilitates the induction of implicit abstraction mechanisms across the stimulus set for the typically developing children; resulting in largely implicit information.

However, there seems to be a degree of explicit learning influences (i.e. sensitivity to bigram information) during AGL, the manipulation of which may improve performance for children with developmental dyslexia. If we consider findings suggesting that children with developmental dyslexia have intact first-order associative learning (Roodenrys & Dunn, 2007) then the introduction of an explicit component (Mathews & Cochran, 1998) in the instruction set may emphasize first-order associative learning and improve children's performance. This possibility, as well as the influence of explicit learning processes (just as in real-life settings), is explored in the following experiment (Experiment 2).

## 5.5 Experiment 2: 'Explicit Instructions'

Experiment 2 examines explicit influences in implicit learning by encouraging the use of explicit learning processes (e.g. memorization processes) during an implicit AGL task. Experiment 2 also examines if explicit information about the training items (Reber, 1976) adds to the acquisition of bigram information and improves implicit learning performance for children with developmental, given that implicit instructions in the previous experiment did not facilitate the learning of fragments for children with dyslexia (chance level performance on both HCS and LCS items). Despite the fact that the instruction set prior to training is more explicit, the task is still considered implicit as the children are not explicitly taught about the exact way the sequences are generated (see Procedure section below).

### 5.5.1 Method

#### 5.5.1.1 Participants

In Experiment 2 a different sample of 34 children (10 girls and 24 boys) was selected, of whom 17 were typically developing (see Table 5.3) and 17 had been diagnosed with developmental dyslexia (see Table 5.4). Their mean age was 10y 6m (SD = 0.94). Experiment 2 used the same selection and matching procedures for the entire sample to that of Experiment 1. Children were chosen from 5 schools of different socio-economic catchment areas in Edinburgh City Council. All formal and ethical procedures were followed (see Appendix A). Children were matched for age, biological sex and classroom. The same inclusion criteria to those of Experiment 1 were used for children with developmental dyslexia and their typically developing peers (in terms of the diagnosis of dyslexia and the basic cognitive and literacy profile of all children) (see section 4.1.1).

**Table 5.3:** Summary of reading and spelling performance.

| Typically developing group | Reading (5-14)[a] | Writing (5-14)[a] |
|---|---|---|
| Child 1 | C(C) | C(C) |
| Child 2 | B(B) | B(B) |
| Child 3 | B(B) | B(B) |
| Child 4 | D(D) | D(D) |
| Child 5 | D(D) | D(D) |
| Child 6 | C(C) | C(C) |
| Child 7 | C(C) | C(C) |
| Child 8 | D(D) | D(C) |
| Child 9 | B(B) | B(C) |
| Child 10 | B(B) | B(B) |
| Child 11 | C(C) | C(C) |
| Child 12 | C(C) | C(C) |
| Child 13 | D(D) | D(D) |
| Child 14 | C(C) | C(C) |
| Child 15 | B(B) | B(B) |
| Child 16 | D(D) | D(D) |
| Child 17 | C(C) | C(C) |

[a]Attainment level on national tests. The scale for primary students ranges from A (being the lowest level of achievement) to E (or above). The brackets indicate the level children should have reached according to their chronological/schooling age.

**Table 5.4:** Summary of reading and spelling performance.

| Dyslexia group | Reading (5-14)[a] | Spelling age[b] |
|---|---|---|
| Child 1 | B (C) | 7years |
| Child 2 | B (C) | 7years |
| Child 3 | A (B) | <6years |
| Child 4 | C (D) | 7years 3months |
| Child 5 | B (C) | 7years 1month |
| Child 6 | B (C) | 7years |
| Child 7 | B (C) | 7 years |
| Child 8 | A (B) | 6years 6months |
| Child 9 | B (D) | 7years 3month |
| Child 10 | C (D) | 7years 7moths |
| Child 11 | B (C) | 7years 1month |
| Child 12 | B (C) | 7years |
| Child 13 | B (C) | 7years 2months |
| Child 14 | B (C) | 7years |
| Child 15 | A (B) | 6years 7months |
| Child 16 | B (C) | 7years |
| Child 17 | C (D) | 8years |

[a] Attainment level based on national tests scores.
[b] Spelling age of children detracted from the administered spelling tests. The hard scores are not reported as spelling tests varied across schools.

#### 5.5.1.2 Materials

Experiment 1 utilizes the alternative grammar (see Appendix F) that Experiment 2 employed. To date, the training stimulus set (i.e. sequences of shapes that had replaced the original sequences of letters) consists of 69 items. All training items are grammatical and are developed by following the permissible transitions of the particular grammar (Knowlton & Squire, 1996; Experimental grammar 1). The training stimulus set is divided in Stimulus order A and Stimulus order B. The testing stimulus set has 32 items, half of which are grammatical (G) and half of which are non-grammatical (NG). The testing stimulus set has an equal number of high and low chunk strength items.

Eight children from each group (i.e. eight typically developing children and eight children with developmental dyslexia) were trained using Stimulus order A and the rest of them (i.e. nine typically developing and 9 developmental dyslexic children) were trained using Stimulus order B.  All children were given the same testing stimulus set

#### 5.5.1.3 Procedure

A similar procedure protocol to that of Experiment 1 was followed for Experiment 2. The researcher welcomed the child and asked him/her to take a seat in front of the computer. A brief conversation took place before the introduction of the task to create a friendly and relaxed atmosphere so that the child did not feel stressed (see Appendix A). Then, the researcher told the child that she/he would be given a computer-based task with geometrical shapes and answered any questions the child had without giving important task-relevant information that could account for performance biases.

The task was held on a portable ACER computer. Prior to the training phase, the child was introduced with the first set of instructions on the computer screen (see Appendix G.4). This time (as opposed to Experiment 1) the instructions informed the child that (a) she/he will see sequences of geometrical shapes the order of which follows a complex set of rules (e.g. only certain shapes can follow other shapes); (b) she/has to try to memorize a big number of items and; (c) it would very useful to try to figure out these rules (i.e. what shapes can follow other shapes) to be able to memorize as many items as possible. The child was asked to read the instructions carefully. Then, the researcher read the instructions aloud, answered questions and moved on to the training phase. The training stimuli were presented in a consecutive order that is one item at a time. Each item remained on screen for 5 seconds until the child had seen 69 items in total. The training phase lasted 6 minutes.

Once the training phase was over, a new set of instructions was introduced. The child was reminded that (a) the sequences she/he has just seen followed very complex rules; (b) she/he was asked to memorize as many items as possible and; (c) it would be helpful to try to figure out the rules. After that, the child was told that she/he would see a new set of items and had to decide whether the news items follow the rules of the old items or not. Next, the child was instructed to say YES if the item followed the rules and NO if the item did not follow the rules. The child was also told that he/she could guess if he/she wasn't sure what the rules were. Finally, the child was informed that the new items would remain on screen until she/he made a decision and was encouraged to respond as quickly as possible. The child was asked to take time to read the instructions; followed by the researcher reading them again out loud. The researcher prompted the child anew to ask any questions[9] before the task began.

After that, the child saw the first testing item and asked to make a grammaticality judgment (i.e. to decide whether the new item followed the same rules with old items). Each item (of the 32 in total) was presented individually. A new item was only introduced once the child gave a YES or a NO answer to the item in question. The researcher recorded the child's answers on paper format. After the completion of the task, the child was asked (post-experimental interview) if she/he noticed a pattern and if she/he used this pattern to make grammaticality judgments. Most of the children (30) replied that they made guesses while only two typically developing children said they had a strategy. Yet, both children were unable to verbalize their strategies.

#### 5.5.1.4 Design

This experiment has a 2 (group: children with dyslexia, typically developing children) X 2 (grammaticality: grammatical, non-grammatical) X 2 (chunk strength: high chunk strength, low chunk strength) mixed design as described in Experiment 1. First, the total number of G and NG items correctly identified as G and NG respectively (Grammaticality) is calculated. Second, the total number of HCS and LCS items (Chunk strength) both G and NG is also calculated.

### 5.5.2 Results

[9] Again, the researcher answered questions in a neutral way to avoid biases towards task-relevant information that could affect the child's performance during the testing phase.

To examine if the new instructional regime affected learning single *t*-tests were run. The *t*-test compared the number of grammatical and non-grammatical items correctly identified as such to chance levels (including both Stimuli order A and Stimuli order B). *T*-test for the typically developing group was significant ($t_{(16)} = 2.94$, $p < 0.05$ $M = 17.71$, SD = 2.4). Typically developing children showed evidence of implicit learning (Pothos & Kirk, 2004; Russeler *et al.,* 2006). Respectively, the *t*-test for the dyslexia group showed that performance did not exceed chance levels ($t_{(16)} = 0.34$, $p > 0.05$ $M = 16.24$, SD = 2.82); thus, children with developmental dyslexia failed to show implicit learning. AGL performance for both groups is depicted in Figure 5.5. The Effect size that was also calculated was large ($d = 0.56$) adding to the significance of *t*-tests results and mitigating the small overlap in performance.

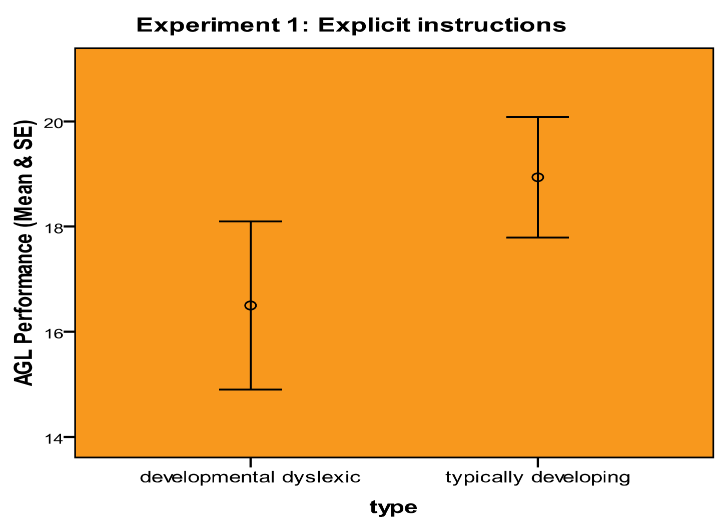


**Figure 5.5** Mean AGL performance (Experiment 2: Explicit instructions) as expressed in terms of the standard error of the mean correct classification judgments.

To further explore the source of the group differences in learning, ANOVA (repeated measures) (group X grammaticality X chunk strength) was run. There was a main effect of grammaticality ($F_{(1,32)} = 6.59$, $p < 0.05$) but there were no group or chunk strength effects: The novel items were more likely to be identified by both groups of children if they were grammatical. Although there was no main effect of group and no 2-way interactions, the 3-way interaction (i.e. when all three variables were taken into consideration) was significant ($F_{(1,32)} = 5.92$, $p < 0.05$) indicating group differences in AGL performance.

To further examine the direction of this noted interaction, single *t*- tests were conducted for each substring dependencies. The *t*-tests compared classification of each type of item against chance. Single *t*-tests were done for (a) G items; NG items; HCS items; LCS items (see figure 5.7); but also for (b) G-HCS items; G-LCS items; NG-HCS items; and NG-LCS items to explore the interaction between grammaticality and chunk strength. For the typically developing group, *t*-tests were significant for G items ($t_{(16)} = 3.6$, $p = 0.002$, $M = 10$ SD = 2.29) and G-LCS items ($t_{(16)} = 4.01$, $p < 0.05$, $M = 5.06$ SD = 1.08): typically developing children identified items primarily based on grammaticality. For the developmental dyslexic group, *t*-test was significant for G items ($t_{(16)} = 3.6$, $p = 0.003$, $M = 9.76$ SD = 2.05), for G-HCS items ($t_{(16)} = 3.43$, $p < 0.05$ $M = 5.06$, SD = 1.06) and for NG-HCS ($t_{(16)} = 3.65$, $p < 0.05$, $M = 6$ SD = 1.93): children with developmental dyslexia classified items mainly based on their associative strength.

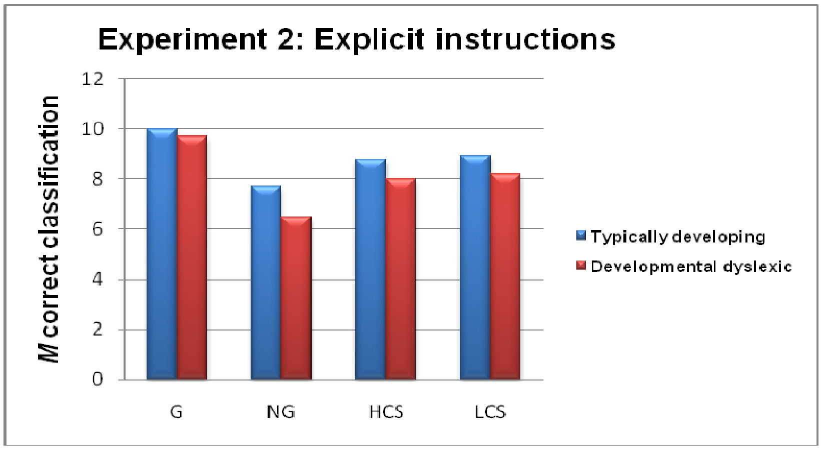


**Figure 5.7** Mean endorsement rate for each stimulus type.

A two-way ANOVA examining group (children with dyslexia, typically developing) X stimulus order (order A, order B) was also employed to examine potential effects of stimulus order on AGL performance. The ANOVA was not significant ($F_{(3,33)} = 2.1$, $p > 0.05$) and thus, stimulus order did not affect classification performance for the two groups.

### 5.5.3 Discussion

Experiment 2 explored (a) implicit learning under a new set of AGL instructions and; (b) if and how explicit learning processes affect implicit learning (as manifested in an alternative AGL task) in typically developing children and children with developmental dyslexia. To facilitate the induction of explicit learning processes during the AGL task children were actively encouraged to memorize items and to discover the underlying rules of the stimuli. Typically developing children showed evidence of learning the grammar (overall above chance performance) whereas children with developmental dyslexia were mainly guessing (chance level performance). On closer examination (ANOVA & single *t*-tests) of how item characteristics (i.e. grammaticality and chunk strength) influenced children's classification judgments a very interesting picture emerged. Typically developing children showed a better performance on grammatical items irrespective of their associative strength (grammaticality) whereas children with developmental dyslexia classified correctly more often grammatical items of high associative strength (i.e. showed some kind of sensitivity towards bigram information). It has to be noted here, that it is not always safe to distinguish between a grammaticality effect and a bias to respond 'yes'. However, the incidental character of the task and pattern of results strongly suggest that the effect found is a grammaticality effect as understood in implicit learning tradition (see Chapter 3).

How can these results be interpreted in relation to implicit learning theory? To begin with, typically developing children showed intact implicit learning manifested in an overall good performance. Children with developmental dyslexia on the other hand, were found impaired in implicit learning despite the fact that the instructions encouraged first-order learning. Children with developmental dyslexia did show some sensitivity to bigram information, but not to such extend to help them cope with the demands of the task. It is very likely that the large number of stimuli to be remembered and the processing time may have imposed a memory span overload (see Chapter 2, section 4.2 on working memory deficit hypothesis for dyslexia). According to Towse *et al.* (1998) processing time provides an important constraint on the amount of information children can retain in their working memory (Towse & Hitch, 1998). This could also explain the lack of associative strength influences on typical children's performance.

Furthermore, the explicit instructions could have led to the formation of rules that are wrong and therefore, do not facilitate performance on the task (Reber, 1989). The instruction set in Experiment 2 probed children to memorize as many items as possible and at the same time alerted them towards the rule-governed nature of the stimuli (i.e. that only certain shapes can follow other shapes). The 'explicit' piece of information about the existence of rules may have encouraged the search for the specific way these rules could be applied (Reber, 1976). However, the memory load along with the search for rules that were probably inappropriate (i.e. children came up with wrong rules) may account (a) for the poor overall performance of children with developmental dyslexia and; (b) for the slightly diminished performance of the typically developing group.

With respect to implicit/explicit interaction the data shows that the kind of learning taking place is largely implicit. This is bolstered by the grammaticality effect that the analysis revealed, which in turn, adds to the discussion over the kind of knowledge children formed during AGL. The results from Experiment 2 reinforce the findings from Experiment 1; that abstract rule-like (i.e. higher-order) knowledge mediates AGL performance for all children (no chunk effect). However, the sensitivity children with developmental dyslexia showed to items of high associative strength indicates a degree of explicit learning influences on implicit learning. Since children with developmental dyslexia are found to associate deficits in both processes (see Chapter 2 & Chapter 4 reviews), the findings suggest that there are developmental differences (other than age) in implicit learning.

To summarize, while typically developing children showed evidence of implicit learning (above chance performance) children with developmental dyslexia did not provide evidence for implicit learning (performance at chance levels). All children showed sensitivity towards both grammaticality and chunk strength (see single *t*-tests). Although children with developmental dyslexia were not clearly facilitated by the introduction of more explicit information, they showed a degree of sensitivity towards bigram information. This indicates some degree of interaction between implicit and explicit learning that may be associated with working memory involvement (see Chapter 2 for working memory deficit hypothesis in dyslexia) during AGL tasks (see Chapter 3 for working memory influences in implicit AGL learning).

### 5.6 Comparison between Experiment 1 and Experiment 2

To establish whether the difference in AGL performance between children with developmental dyslexia and typically developing children was consistent across the two experiments, two-way ANOVA was employed. The comparison was run to examine if children's implicit learning performance changed depending on the nature of information they received.

### 5.6.1 Results

Two-way ANOVA ($F_{(3,65)} = 3.44$, $p < 0.05$) examining group (children with dyslexia, typically developing) X experiment (Experiment 1:implicit instructions, Experiment 2:explicit instructions) revealed a main effect of group ($F_{(3,65)} = 8.64$, $p < 0.05$) but no effect of experiment or an interaction effect. As shown above (see *t*-test results in

Experiment 1 and Experiment 2) children with developmental dyslexia scored more poorly than typically developing children under both experimental regimes.

### 5.6.2 Discussion

The finding that the type of instructions did not have a detrimental effect on either group of children indicates that implicit learning abilities are consistently diminished for children with developmental dyslexia irrespective of the nature of the instructions. The active encouragement to use explicit learning processes (i.e. the instruction to memorize) did not have a critical impact on developmental dyslexic children's performance. Maybe the big number of items to be memorized and the possible accompanying working memory problems can account for the present findings (see General Discussion below). Contrary, typically developing children show intact implicit learning abilities irrespective of the kind of instructions they receive.

The indication that more explicit information does not enhance implicit learning performance for children with developmental dyslexia has an indirect link with learning theories and teaching strategies. It questions the effectiveness of naturalistic learning theories and practices in individuals with learning difficulties (Graham, 2000) and has implications for teaching in such groups (more extended discussion takes place in Chapter 8).

## 5.7 General Discussion

The aim of Study 1 of the thesis was twofold: First, to explore for the first time implicit learning abilities in children with developmental dyslexia in a highly complex learning environment as reflected in AGL. Second, Study 1 tested how robust implicit learning is in childhood and if it is affected by developmental factors other than age by comparing performance between typically developing children and children with developmental dyslexia. Implicit learning was examined in two AGL experiments (Experiment 1: implicit instructions; Experiment 2: Explicit instructions) that differed in terms of the nature and timing of the instruction set. Performance on the AGL task was measured separately for the two groups of children (in both experiments) to serve two separate purposes: First, to compare the overall performance of typically developing children with that of children with developmental dyslexia under the same set of instructions and second, to compare the performance of each group of children under a different set of instructions.

Overall, children with developmental dyslexia failed to show implicit learning reflected in AGL as opposed to typically developing children who showed intact implicit learning. Study 1 of the thesis contradicts other studies that report intact implicit learning in children populations (Roodenrys & Dunn, 2007), however it agrees with other studies in adult populations that argue in favor of a specific implicit learning deficit, namely a deficit in implicit higher-order learning (Bennett *et al*., 2008; Howard *et al*., 2006). Thus, the findings from Study 1 suggest that children with developmental dyslexia have impairments in abstract rule-learning; abstract rule learning is considered a prerequisite for successful AGL performance (Sallas *et al*., 2007). This could explain why children with developmental dyslexia are found spared in simple associative implicit learning (Roodenrys & Dunn, 2007; but see also Vicari *et al*., 2003, 2005) and can cope with the demands of everyday life that require a blend of implicit and explicit learning (Pothos & Kirk, 2004).

At a theoretical level, two major inferences can be drawn from Study 1 results. First, and most importantly, there may be developmental influences (other than age) on implicit rule-learning in childhood. While basic implicit learning abilities (e.g. first-order learning) proceed and develop efficiently in childhood (Meulemans *et al.,* 1998; Roodenrys & Dunn, 2007) irrespective of developmental limitations, this may not to be the case with more sophisticated implicit learning abilities (e.g. abstract rule-learning). Study 1, therefore, argues that implicit learning abilities may vary in childhood in cases when we have a different developmental profile.

Because the Knowlton & Squire's (1996) grammar is constructed in such a way to minimize explicit effects that are associated with similarity (Redington & Chater, 1996) participants' performance primarily reflects learning of deep structure (rule learning) (e.g. Manza & Reber, 1994) instead of learning of specific instances (e.g. Perruchet & Pacteau, 1990) that are compared to training items (e.g. Brooks & Vokey, 1991). However, other explicit factors such as working memory constraints (i.e. memory overload, Towse, Hitch & Hutton, 1998 and potential working memory deficits, Baddeley, 1998) may hinder implicit higher-order learning in children in developmental dyslexia. Thus, implicit and explicit factors need to be attributed independently and be manipulated experimentally. This way, explicit learning processes related to working memory (Seger, 1994) in AGL (and consequently to implicit learning) will become more clear.

Second, Study 1 adds important information to the discussion over the kind of information children acquire during AGL and consequently, over the learning (i.e. the learning processes) that AGL calls on. The findings from Study 1 suggest that the learning taking place in AGL is (a) largely implicit; (b) is probabilistic in the sense that good performance requires the learning of higher-order dependencies as opposed to deterministic learning (i.e. the learning of first-order dependencies) in simple SRTT (e.g. simple cued recognition task). The inherent regularities in the AGL structure are thought to induce abstraction mechanisms (e.g. the AGL transfer phenomenon, see Chapter 3, section 6) so, AGL performance can be used as an indirect way of examining how abstraction processes develop in typical and atypical childhood (e.g. children with developmental dyslexia).

AGL can be more extensively used for exploring developmental influences in higher-order implicit learning (and its resulting knowledge) in childhood by constructing more appropriate variations for children (e.g. lowering the cognitive demands and adopting a different learning procedure). If children with developmental dyslexia are consistently found impaired in implicit learning as tested in AGL then this can partially explain (a) their reading problems and; (b) the inability to become fluent readers even when explicit phonological abilities are good. A deficit in implicit higher-order learning may diminish the sensitivity to the structural regularities of phonological information (Gombert, 2003). Given the well-established relationship between phonology and reading (e.g. Swanson & Jerman, 2007) problems in the establishment of fully flexible phonological abilities has a knock-on effect in reading; a combined implicit and phonological deficit (Snowling,

2000) might partially account for the academic problems children with developmental dyslexia experience.

In these cases of children with good phonological abilities on the other hand, an implicit learning deficit may result in fluency problems (Wimmer, Mayringer, & Landerl, 2000). An implicit learning deficit could prevent reading from becoming an automatic procedure (see Chapter 2, section 4.1 for automatization deficit hypothesis of dyslexia) and explain why children with developmental dyslexia do not reach a high degree of reading fluency (e.g. Sperling *et. al*, 2004; Paulesu *et al*., 2001; Wimmer *et al*., 2000).

### 5.8 Summary

Taken together, the findings from the first two experiments of the thesis provide important evidence for an implicit learning deficit in children with developmental dyslexia. This implicit learning deficit seems to be associated with higher-order learning abilities as manifested in the grammaticality effect that mediated performance for the typically developing children. But the data from Study 1 also suggests that there may be explicit influences (i.e. working memory constraints) on implicit learning performance (i.e. the sensitivity children with developmental dyslexia showed to fragment information as *t*-tests revealed). These explicit factors affecting implicit learning are in all probabilities related to working memory functions (see p. 53) and could question the likelihood of a 'true' learning deficit as reflected in Study's 1 results. By controlling (experimentally) for explicit and implicit learning factors independently, we can explore whether the failure children with developmental dyslexia show in AGL constitutes a ‘learning problem’ (i.e. inability to acquire knowledge) or a ‘performance problem’ (i.e. inability to retrieve knowledge) (Perlman & Tzelgov, 2006).

AGL provides us with means to explore implicit and explicit learning factors independently. Its recognized advantages of being able to tap into cognitive and abstract representation processes (Reber, Martinez & Weintraub, 2003) more effectively than other implicit learning paradigms make AGL advantageous in the study of implicit higher-order learning in developmental dyslexia. In the light of this, the thesis will continue to use the AGL paradigm. The following Study 2, uses a variant of the paradigm that is more ‘child-friendly’ and an experimental design that controls for working memory influences independently.

# CHAPTER 6

# STUDY 2[10]: DO CHILDREN WITH DEVELOPMENTAL DYSLEXIA HAVE IMPAIRMENTS IN IMPLICIT LEARNING?

## 6.1 Aims of Chapter

Chapter 6 presents the second study of the thesis. Study 2 explores higher-order implicit learning using an alternative AGL in which working memory involvement is systematically controlled. Working memory has been implicated in both developmental dyslexia theory (see Chapter 2, section 4.2) and implicit learning theory (i.e. studies implicate the executive component of Baddeley's (1988, 2000, 2003) working memory system in hierarchical learning (Curran & Keele, 1993)). The experimental control for working memory influences allows a more thorough examination of implicit and explicit influences during implicit learning tasks. Implicit learning and explicit learning can be attributed independently and be assessed by different measures of performance. This will enable a systematic examination of implicit learning and its resulting knowledge in typically developing children and children with developmental dyslexia. As stated in the previous chapter, the thesis will continue to use the AGL paradigm because its inherent complex sequential structure calls on higher-order learning (Seger, 1994).

## 6.2 Introduction

Given that Study 1 of the thesis is the first to use the AGL paradigm in school-aged children with developmental dyslexia, it is important to summarize the methodology and

[10] The data from the current study has been published in *Dyslexia* (see Appendix I)

results. Two versions of an AGL task were used that varied in the timing and nature of the instruction set. Children were asked to either observe the training stimuli (Experiment 1: Implicit instructions) or try to memorize as many stimuli as they could (Experiment 2: Explicit instructions). Then children were exposed to novel testing items. This design facilitated (a) examination of implicit learning abilities under more complex implicit learning conditions than had previously been tested; (b) the investigation of possible interactions between implicit and explicit influences during AGL. Therefore, Study 1 not only provides the first set of data on how higher-order implicit learning abilities develop in typical and atypical childhood but also sets the ground to investigate more thoroughly the degree of explicit influences during implicit learning.

Typical children showed intact implicit learning in accord with previous studies that included typical children as participants (Don *et al*., 2003; Gomez & Gerken, 1998; Marcus *et al*., 1999; Meulemans *et al.,* 1998; Vinter & Perruchet, 2000). By contrast, children with developmental dyslexia were found impaired in implicit learning. Most importantly, Study 1 data suggests that AGL learning is primarily abstract and results to rule-like knowledge. Thus, children with developmental dyslexia are found impaired in implicit, possibly rule-like learning (i.e. higher-order learning); children with developmental dyslexia face problems with the implicit abstraction of knowledge across serially presented stimuli.

However, Study 1 indicates that there may be explicit learning factors mediating AGL (sensitivity to bigram information) that could be held partially responsible for the failure children with developmental dyslexia show in AGL performance. These explicit learning factors seem to be associated with working memory constraints; both in terms of memory load and of potential working memory deficits. This raises the question of whether a variation of AGL task can be created in such a way to (a) suit children's cognitive load capacities (e.g. Towse *et al*., 1998) and; (b) systematically control for working memory influences. By doing this, we can explore whether the implicit learning deficit Study 1 revealed reflects a 'true' implicit learning deficit or whether it is largely the result of explicit memory constraints.

### 6.3 The present study

The current study uses AGL but with adaptations. In particular, the study utilizes the AGL task presented in Study 1 (Chapter 5) but modified to control for working memory requirements more effectively. In this way, the role of explicit (i.e. working memory influences) and implicit learning can be attributed independently (Russeler *et al*., 2006). When explicit learning abilities are more carefully controlled then, in turn, the share of more sophisticated implicit learning abilities in the etiology of developmental dyslexia can be investigated more profoundly.

Working memory load is controlled in two ways. First, a new technique is adopted during training phase, the perfect free recall (PFR) task (Russeler *et al*., 2006). PFR is an alternate of free recall (i.e. an explicit memory test that is often administered to amnesic patients during which participants try to recall items recently presented without the help of cues, Schacter, 1992). It has to be noted here that PFR is primarily a measure of explicit learning (i.e. a measure of working memory influences, Russeler *et al*., 2006). However, evidence from adult research (Russeler *et al*., 2006) suggests that participants in PFR tasks seem to benefit from the exploitation of the underlying regularities as the training items are highly structured. Therefore, PFR can be also considered as another measure of learning of the grammatical structure (Russeler *et al*., 2006).

Second, the materials are modified by lowering the number of training and testing items as well as the constituent elements of the items in the stimulus set in use. Thus, the task is now thought to be more suitable and appropriate for children as it reduces the memory load (in terms of the length and format of the task itself and the amount of anxiety and fatigue that it may release). For the testing phase, two measures of grammaticality (i.e. grammaticality judgments for new items and post-experimental interviews) are used.

Two major research questions are explored in Study 2. First, do children with developmental dyslexia require the same number of trials as their non-dyslexic peers to achieve PFR in the training phase? In Russeler *et al*.'s (2006) study, which uses a similar PFR technique, adults with developmental dyslexia required the same amount of exposure to exemplars as adults without developmental dyslexia before they could correctly recall the sequences. Second, do children with developmental dyslexia perform as well as typically developing children in the testing phase of the modified AGL task once they have achieved PFR? This would support the argument that children with developmental dyslexia were able to use the implicit knowledge established during the training phase to improve performance on the grammaticality judgment task.

## 6.4 Method

### 6.4.1 Participants

The 32 primary school children who participated in the present study were recruited from two primary schools in the City of Edinburgh Council (Scotland). The same standard procedures were followed for the selection and approach of children (see Appendix A) as in Study 1. Children were between nine to twelve years old. First, the dyslexia sample was selected. Sixteen of the participating children were described either as having developmental dyslexia or as being in suspicion of dyslexia based on formal diagnostic criteria[11].

To establish developmental dyslexia in the sample, reading and spelling tests and standardized cognitive measures were employed. Reading and spelling abilities were measured using the Basic Reading and Spelling subtests from the Word Test (1993) (see Table 6.2). Their reading age (*M* = 7y 1m) was two years below their chronologic age (*M* = 9y 4m) (see Table 6.1). To assess basic cognitive abilities four subcomponents of the WISC IV (4th edition) (Digit Span, Matrix reasoning, Similarities, Cancellation and Symbol Search) were administered (see Table 6.2). All the children had average or above average cognitive abilities. It has to be stressed at this point that the thesis did not opt for a comprehensive screening of all the abilities of the children for three main reasons: (a) children are comprehensively screened throughout the school year; (b) on the basis of the argument that IQ does not measure all available abilities (Miles, 1996; Siegel, 1992), it was decided to measure basic verbal and non-verbal abilities as means to further establish differences between the two groups of children and; (c) the administration of the

[11] There is a typical diagnostic procedure followed by each appointed education psychologist that applies for all state/private schools in Scotland: children are given a standardized battery of dyslexia screening tests (e.g. Nelson's dyslexia screener) along with other cognitive measures (e,g. Raven's matrices).

measures took place during school hours so, there wasn't enough time for a detailed screening of children's cognitive and literacy abilities (see Chapter 2 section 3.3).

**Table 6.1:** Summary of literacy abilities

| GROUP | N | CA | RA | SA |
|---|---|---|---|---|
| **Dyslexic** | 16 | 9y 4m | 7y 1m | > 6y |
| **Typically developing** | 16 | 9y 3m | 9y 6m | 8y 2m |

NOTE: The values represent means of chronological age, reading age and spelling age.

The children that comprised the dyslexia group were then matched with typically developing children in a variety of characteristics. They were matched according to their chronological age and their sex. They were also selected from the same classrooms so that emerging differences could not be easily attributed to environmental factors (such as different teaching); in this way such differences would be counterbalanced across the sample. The children that comprised the typically developing group were given the same battery of tests as children with developmental dyslexia. Their reading ($M$ = 9y 6m) and spelling (M= 8y 2m) ages were in line with their chronological age ($M$ = 9y 3m) (see Table 6.1). All typically developing children had average (or above average) cognitive and literacy abilities (see Table 6.2). The selection of typical children was based on the cognitive profile of children with dyslexia; children were matched on their basic cognitive abilities to control for possible IQ influences on implicit learning performance.

All participating children had normal or corrected to normal vision while no other existing problems were reported. School and parental consents were obtained for all the children that took part in the study. They were all native speakers of English and had no previous experience with cognitive experiments.

**Table 6.2:** WISC and WORD raw scores

| GROUP | DS | MR | SIM | CAN | SMS | PS | BR | SP |
|---|---|---|---|---|---|---|---|---|
| **Dyslexic** | 13.94 | 12.1 | 15.00 | 67.81 | 21.25 | 89.09 | 20.50 | 9.19 |
| **Typical** | 15.44 | 13.8 | 18.94 | 66.00 | 23.25 | 89.25 | 37.00 | 17.81 |
| **P value** | 0.89 | 0.22 | 0.11 | 0.33 | 0.22 | 0.98 | 0.00* | 0.00* |

NOTE: the values represent mean for WISC Digit Span, Matrix Reasoning, Similarities, Cancellation, Symbol Search, Processing Speed, and WORD Basic Reading and Spelling.
*$p < 0.001$

### 6.4.2 Materials

#### 6.4.2.1 The Artificial Grammar Learning task

The AGL task that was chosen was developed from Knowlton and Squire (1996) Experiment Grammar 1 (see Chapter 5, Figure 5.1) as in the previous Study 1. Using Knowlton and Squire's (1996) original grammar, 18 grammatical (G) and 10 non-grammatical (NG) items were created following the grammar's *IN* and *OUT* arrows. The NG items were constructed by introducing one error in each of the G items. The G and NG items were matched in chunk strength having an equal number of *low* chunk strength (LCS) and *high* chunk strength (HCS) items (half of the items had low and half of them high chunk strength). Chunk strength (see Appendix G.2) for each testing item was calculated by dividing the total number of bigrams and trigrams it consisted of, with the number of times these bigrams and trigrams had appeared during the training phase.

To construct the alternative grammar the sequences of letters of Knowlton & Squire's (1996) grammar were replaced with geometrical shapes as follows: X = rectangular, V =

circle, T = triangle and J = square (see Figure 6.1). The sequences of shapes were composed of between two and five elements. The slightly reduced length of the sequences was thought to lower the cognitive load of the task required to complete the task: Shorter items were chosen to reduce the processing time of the stimuli (e.g. Towse *et al*., 1998). The task format was now more ‘child friendly’.

Overall, eight of the G sequences were used as training items in the perfect free recall task and the twenty remaining novel G and NG sequences were utilized as testing items. The resulting testing stimulus set had an equal number of G and NG items balanced for chunk strength.

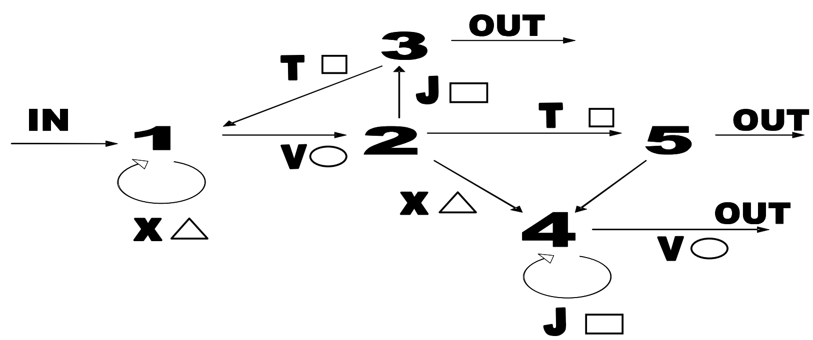


**Figure 6.1** The experimental grammar as developed from Knowlton and Squire (1996). The letters are replaced with shapes as follows: X = triangle, V = circle, T = square and J = rectangle.

### 6.4.3 Procedure

The researcher welcomed the child and asked him/her to take a seat. Prior to the experiment a brief conversation took place so that the child felt relaxed and was familiarized with the experimental setting. Then, the researcher described in a few words what was about to happen: She informed the child that she/he would be asked to memorize sequences of shapes and then perform a computer task. The child was told that she/he could opt out at any time during the task (see Appendix A).

The task was divided into two phases, the training and the testing phase. During the training phase, the child was shown four cards that each had two sequences printed on it. The cards contained progressively more difficult sequences of shapes in terms of length (see Appendix G.1). Each card was presented for 15 seconds and the child was asked to memorize and reproduce the depicted sequences freely (PFR) (see Appendix G.3) using the provided printed cards of individual shapes[12]. If the child did not manage to reproduce the sequences accurately with the first attempt, the card was shown for another 15 seconds; this was repeated until the child reproduced correctly the sequences depicted on each of the four cards. The researcher recorded the trials that the child required to achieve perfect recall on paper format. The use of printed cards instead of electronic ones for the training phase was selected in order to increase the trust in the researcher (Reber, 1967).

Immediately after the training phase (PFR), the child was informed about the rule-governed nature of the stimuli she/he had just memorized. Then, she/he was told that the second phase would now begin and this would be performed on the computer. The child was notified that she/he will see new items and has to make grammaticality judgments: To decide which of the newly presented items followed the same rules as the previously memorized items and which did not conform to these rules (see Appendix G. 3). The stimuli were presented on an ACER portable computer screen and remained on screen

[12] We chose to provide printed cards instead of asking the children to draw the sequences for two main reasons: First, to avoid any motor engagement during the task and second, to reduce the duration of the task as this was administered during school times and in turn, to minimize the amount of fatigue.

until the child gave an answer. The researcher recorded the child's answers on paper format.

Once the training and testing phases were completed, the child was asked whether she/he noticed a specific pattern (or formed a rule) that she/he used to make grammaticality judgments during testing phase. The majority of the children replied that they guessed whilst the few (i.e. three children out of the 32) who attempted to describe (to verbalize) the pattern they followed, they were restricted to merely pointing out some shape combinations. However, none of the applied 'rules' were correct.

### 6.4.4 Design

In the present study, performance on the AGL task was calculated via two dependent variables: A perfect free recall (PFR) score and a grammaticality judgment score. In the training phase, the number of trials required for PFR of the two items depicted on each of the four cards was calculated separately for each child. Subsequently, PFR performance of each group of children was compared against each other to investigate if the two groups differed in the amount of exposure needed to successfully memorize the structured items.

Grammaticality judgment scores were calculated during the testing phase. In the testing phase children were asked to make grammaticality judgments for novel strings of shapes i.e. to decide whether the new strings conformed to the rules of the grammar they had previously been exposed to. The stimuli were constructed according to a 2 X 2 crossed design: Grammaticality (G items, NG items) and chunk strength (high chunk strength (HCS) items, low chunk strength (LCS) items). Grammaticality judgment scores were calculated for all items (1) as a total score of correctly identified grammatical and non-grammatical items, and (2) as a total score of each of the 4 conditions separately (G-HCS, G-LCS, NG-HCS and NG-LCS). There was one participant type variable with two levels (children with developmental dyslexia, typically developing children); this was fully crossed with the stimuli variables.

### 6.5 Results

The first research question was whether children with developmental dyslexia would require the same amount of exposure to successfully memorize the training items compared to the typically developing children. To investigate this, an independent *t*-test was run comparing the mean number of trials typically developing children required for PFR to that of developmental dyslexics'. The *t*-test showed no difference between the PFR scores of each group ($t_{(30)} = 1.620$, $p > 0.05$): children with developmental dyslexia required the same number of trials until PFR was achieved as typically developing children.

As the cards became progressively more difficult, it was decided to see whether a difference existed at particular levels of difficulty. Thus, each card was tested separately using a paired *t*-test to compare the mean number of trials required for PFR of each card between the two groups. The paired *t*-test was not significant (card 1: $t_{(15)} = 0.696$, $p > 0.05$, card 2: $t_{(15)} = 0.000$, $p > 0.05$, card 3: $t_{(15)} = 1.627$, $p > 0.05$ and card 4: $t_{(15)} = 1.962$, $p > 0.05$) for any of the four cards: children with developmental dyslexia did not require more trials compared to typically developing children to memorize the training exemplars (see Figure 6.2).

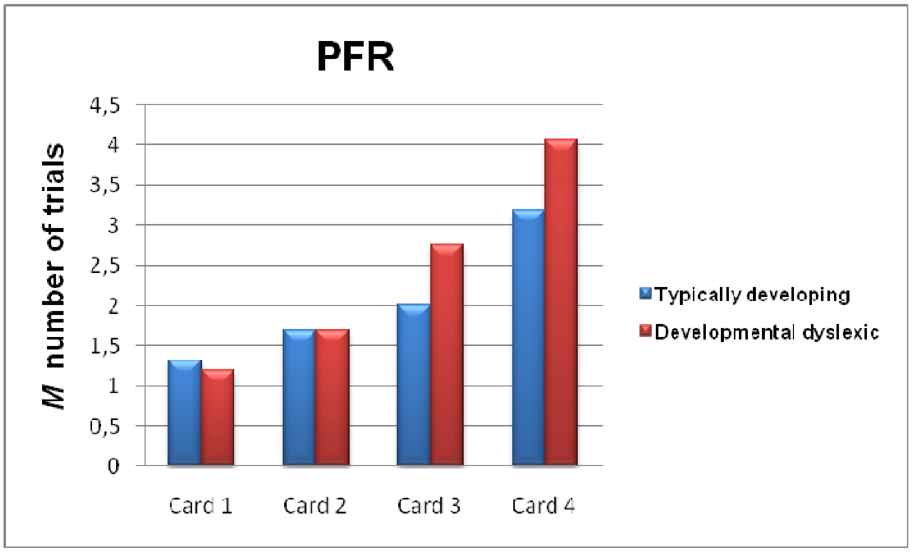


**Figure 6.2** The mean number of trials required per card for each group to freely reproduce the displayed sequences.

Second, children's performance was assessed during the testing phase and the two groups' performance was compared against each other using various statistical analyses for different levels of interest. To test if there were differences in the overall performance of the groups we employed two different statistical tests. First, separate one sample *t*-tests were run comparing each group's total number of correct responses (G and NG of both HCS and LCS) against chance level (see also Knowlton & Squire, 1994, 1996; Pothos & Kirk, 2004; Russeler *et al.*, 2006). In our task, maximum performance would be 20, minimum performance would be 0 and chance performance would be 10.

The *t*-test for typically developing children was significant ($t_{(15)} = 2.40$, $p < 0.05$, $M = 11.06$ SD = 1.8). Typically developing children were able to successfully identify both grammatical and non-grammatical items more often than would be predicted by chance. In contrast, children with developmental dyslexia responded at chance level ($t_{(15)} = 0.51$,

$p > 0.05$, $M = 9.75$ SD = 1.95). They were not able to identify G and NG items at above chance rates. Although typically developing children did not exhibit a very high performance (55%), it is within the expected AGL levels of performance that usually vary from 55% to 65%. Overall, AGL performance for both groups is shown in Figure 6.3.

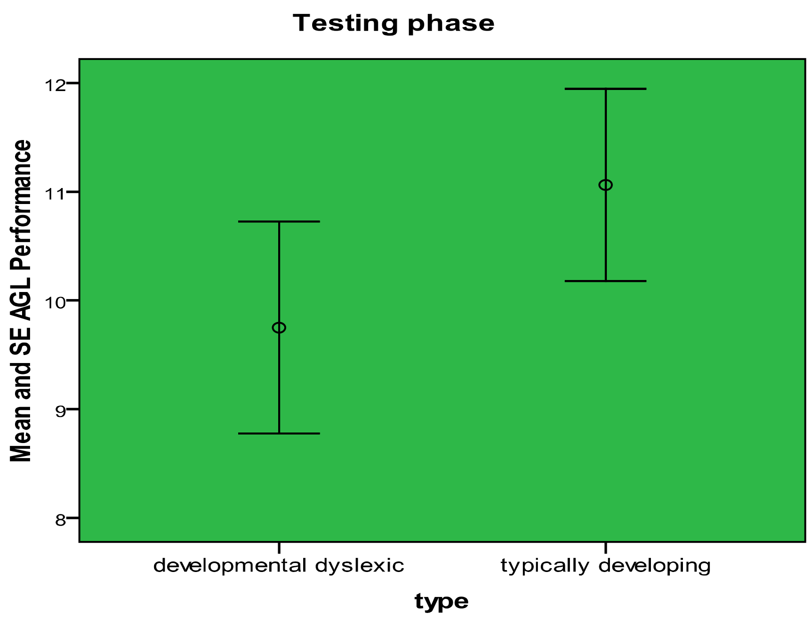


**Figure 6.3** AGL performance expressed as the standard error of mean correct classification judgments.

Given that (a) the sample was carefully matched and (b) typically developing children's performance was at the lower end of expected AGL performance, it was decided to run an additional paired *t*-test to compare the mean performance on AGL task for each pair of children. The paired *t*-test showed that the difference between the mean performance in the AGL task of the two groups was significant ($t_{(15)} = 10.859$, $p = 0.000$, $M = 5.31$ SD

=1.957). Children with developmental dyslexia performed significantly lower compared to their typically developing pairs.

The Effect size (Cohen's d) was calculated in order to further assess the degree of significance obtained by the *t*-test for the performance of the typically developing group compared to the performance of the dyslexic group during the testing phase. The effect size was large ($d$ = 0.7) and thus the performance of the two groups of children was substantially different; this also moderates the relatively large overlap in performance (as reflected in the groups error rates, see Figure 6.3 above).

To explore the difference in the overall performance of the groups more thoroughly an ANOVA (repeated measures) was employed, with one factor corresponding to participant type (dyslexic, typically developing), a second one to grammaticality (G, NG) and a third one to chunk strength (HCS, LCS). The Between Subjects ANOVA revealed a main effect of participant type ($F_{(1,30)} = 4.521$, $p < 0.05$): Children with developmental children scored significantly lower compared to typically developing children; the independent *t*-tests previously employed augment the group effect. Within Subjects ANOVA showed a main effect of grammaticality ($F_{(1,30)} = 6.548$, $p < 0.05$) and a main effect of chunk strength ($F_{(1,30)} = 11.01$, $p < 0.05$) so that G items ($M$ = 2.69, SD = 1.15) and NG ($M$ = 3.1, SD = 1.10) of HCS elicited more correct responses compared to G ($M$ = 1.75, SD = 1.24) and NG ($M$ = 2.88, SD = 1.24) items of LCS for all children. There were no 2-way or 3-way interactions between the three variables.

To examine whether this difference in performance between the two groups of children was consistent across the specific substring dependencies i.e. grammaticality (G or NG irrespectively of CS) and chunk strength (HCS or LCS irrespectively of grammaticality) paired *t*-tests were employed for all four descriptive levels of the stimuli (G, NG, HCS and LCS). The paired *t*-tests were significant for G items ($t_{(15)} = 2.26$ $p < 0.05$, $M = 1.13$ SD = 1.99) and HCS items ($t_{(15)} = 2.27$ $p < 0.05$, $M = 0.89$ SD = 1.54): children with developmental dyslexia performed consistently lower when the stimuli where grammatical. Both groups' performance on the four different types of stimuli is depicted in figure 6.4 as the mean number of correctly identified stimuli.

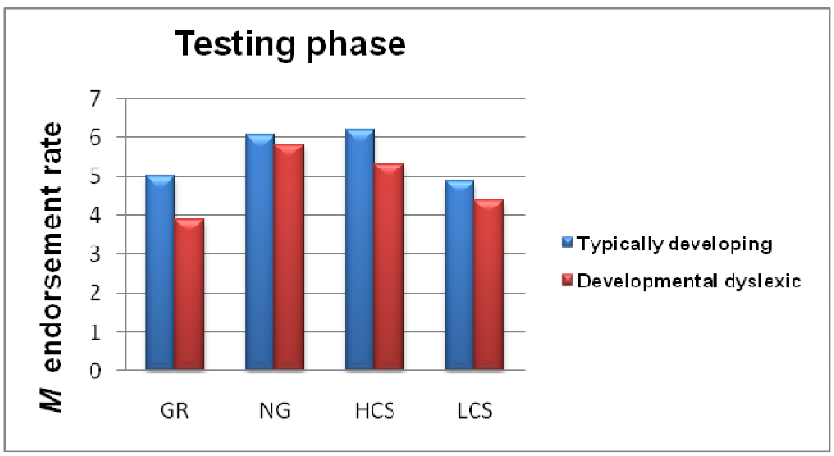


**Figure 6.4** Mean classification rates for each type of item separately for each group of participants.

### 6.6 Discussion

The purpose of Study 2 was to investigate implicit learning (and the resulting knowledge) in children with and without developmental dyslexia using a modified AGL task that controls for working memory influences. Different measures of performance were used to explore more systematically explicit and implicit learning processes in highly complex learning environments. More specific, it was investigated whether both groups of children would require the same amount of exposure to learn the training items and consequently whether they would be able to use this knowledge to meet the demands of the implicit task. The results from the current study can be summarized in two main findings: a) typically developing children show intact implicit learning whereas children with developmental dyslexia are found impaired and b) AGL is mediated by both rule-like and fragment-based learning (and thus, results in both abstract and specific knowledge respectively).

Although the nature of the acquired knowledge, either implicit (Ashby, Alfonso- Reese, Turken, & Waldron, 1998; Reber, 1993; Sperling *et al.,* 2004) or explicit (Dulany *et al*., 1984; Perruchet & Pacteau, 1991) is still debatable in AGL tasks (see Chapter 3) it was assumed that the type of learning that has been explored during the AGL task was mainly implicit; both groups were exposed to testing items that differed from the training items (i.e. testing strings were novel sequences created from the same grammar as the training items). Moreover, the fact that none of the children could verbalize the criteria upon which they based their selections during the training phase further attests to the aforementioned assumption (see Chapter 3, section 3 on criteria of implicit learning). Although learning was primarily implicit, the grammaticality and chunk-strength effects that were established indicate that both rule-like and fragment-based knowledge mediated AGL performance. The fact that typical children were able to identify grammatical and non-grammatical items at above chance rates serves as an indication of abstract rule learning taking place (see Chapter 3). At the same time the fact that the associative strength of the items influenced decisions during testing phase, points to specific knowledge being formulated: children were able to learning some fragment-based knowledge (chunk strength effect), which they used to make judgments about the novel testing items (Perruchet & Pacteau, 1991).

The first research question Study 2 explored was whether children with developmental dyslexia will show the same PFR performance as typically developing children, in line with previous research in adults (see Russeler et al., 2006). Indeed, both groups of children required the same amount of exposure to learn the training strings. The present results therefore, suggest that the structured nature of the stimuli helped all children to exhibit the same learning effect. Despite the fact that children with developmental dyslexia have been linked to memory deficits (e.g. Swanson & Jerman, 2007), it seems they have benefited from their exposure to the structured environment to enhance their perfect free recall; the exploitation of the stimulus regularities facilitated their working memory performance (Russeler et al., 2006). Hence, any failure during the testing phase could not be attributed to impoverished (partial) memorization of the items (Pothos, 2007). In other words, failure to cope with the demands of the implicit task could not be attributed to explicit influences (i.e. poor explicit memorization of training items). Given that tasks are not process pure in the sense that there may be some explicit influences during implicit learning tasks, the control for working memory and the training procedure that required the free recall of all training items, minimized such effects. [It needs to be said at this point that children with developmental dyslexia were matched for working memory capacity (as reflected in the mean Digit Span score, see Table 6.2) with their typically developing pairs, however there was variance in individual abilities amongst the dyslexia group].

The fact that both groups of children exhibited the same learning effect in terms of the amount of exposure needed to memorize the grammatical sequences during the training phase, led to the expectation that all children would show similar classification performance during the testing phase. However, children with developmental dyslexia scored poorly. In contrast, typically developing children scored at above chance rates showing intact implicit learning. While typically developing children seemed to have used the previously acquired knowledge (PRF) to give correct responses (i.e. to successfully distinguish between grammatical and non-grammatical items), this was not the case for children with developmental dyslexia.

The specific instances or exemplars (i.e. the training items) play an important role in learning as they act as accumulative events that facilitate the emergence of the rules (McClelland & Rumelhart, 1985). Learning can take place not only by exploiting the explicit knowledge but also the commonalities in the pattern and the statistical relationship between the displayed elements, which allow the elicitation of generalization processes (Rumelhart & McClelland, 1986b). Likewise, children need to form more abstract and conceptual representations and some rule knowledge to cope with the demands of the task (Reber *et al.*, 2003) because the stimuli are very similar in their surface features. [It has to be noted that it is not really puzzling that the classification of NG is higher than G (see fig. 6.4) as both NG and G items refer to grammaticality: children are asked to correctly identify both grammatical and non-grammatical items; ability to do so, points to the abstraction of implicit rules that can be used to make judgments about both types of items].

However, the finding that children with developmental dyslexia were able to preserve specific items (PRF and chunk strength effect) but failed to use this knowledge to make grammaticality judgments boosts the findings from Study 1 of the thesis, which suggest that children with developmental dyslexia may be facing problems with abstracting information. In other words, if children with developmental dyslexia face a performance problem (i.e. while they are able to abstract the regularities across the items to be memorized, they cannot use the abstracted information in full) one would expect that they would show evidence of implicit learning (i.e. lower but still above chance performance, Pothos & Kirk, 2004). Yet, children with developmental dyslexia did not show evidence of implicit learning (chance level performance) and thus, seem to face a learning problem; despite the fact that they memorized the training stimuli, they were not able to abstract the inbuilt regularities.

With regard to the kind of knowledge children acquired during AGL, the data show that both rule-like and fragment-based knowledge (Perruchet & Pacteau, 1991; Vinter & Perruchet, 2000) mediated AGL performance. The results do not come as a surprise in relation to the relevant literature. It has been argued that for highly accurate performance in AGL tasks the acquisition of implicit rules is mandatory (Dienes, 1992; Sallas *et al*., 2007). At the same time, the experimental regime that was adopted enhanced the possibility of fragment influences (e.g. Dulany *et al*., 1985) as the children were explicitly asked to memorize and reproduce the training items. The experimental procedure emphasized lower (constituent element) and mid-level knowledge (bigrams and/or trigrams). The pattern of results suggests that children with developmental dyslexia have difficulties in the abstraction of information but most likely they do not face problems in the representation and reproduction of fragment knowledge.

As discussed in the previous chapter (Study 1), reading is an analogy of a highly complex and structured learning condition. The extraction of regularities is considered essential for the successful establishment of good orthographic-phonological mappings and good overall phonological abilities (Sperling *et al*., 2004; Howard *et al*., 200; see also Chapter 2, section 3.2). Typical children are found to be sensitive in non-explicitly taught orthographic regularities (Cassar & Treiman, 1997) and in structural features of the written system (Gombert, 2003). In contrast, Study 2 showed that children with developmental dyslexia are not sensitive towards the regularities of a structured environment (as manifested in the AGL task in use). As discussed in Chapter 2 (section 4.2), due to the close relationship between successful reading and phonology, reading impairments in developmental dyslexia are considered indicators of a core phonological deficit (Snowling, 2000). Therefore, a phonological deficit combined with an implicit learning deficit could account for a failure to apply statistical rules in grapheme-phoneme correspondences resulting in the consistently observed reading difficulties in dyslexic populations (Sperling *et al*., 2004).

Given that implicit learning is considered an automatic process (Seger, 1994) (see pp.16-17) and in turn, developmental dyslexia has been associated with automatization deficits (e.g. Nicolson & Fawcett, 1990) it seems plausible that an implicit learning deficit may prevent reading from becoming an automatic procedure and explain why children with developmental dyslexia do not reach a high degree of reading fluency (e.g. Sperling *et. al*, 2004; Paulesu *et al*., 2001; Wimmer *et al*., 2000) even in cases where it can be shown that they have good phonological abilities.

The results from this study provide a small contribution to the debate over the degree of interaction between implicit and explicit learning (Seger, 1994). The present study revealed an implicit and explicit learning dissociation: children with developmental dyslexia showed an implicit learning deficit in the presence of good explicit learning (as manifested in the PFR scores). This dissociation between some specific implicit and explicit learning processes has two indirect implications; one for developmental dyslexia theory and one for implicit learning theory. First, it adds weight to the suggestion that implicit learning deficits can be found in populations with developmental dyslexia even when explicit learning abilities are spared (Folia *et al*., 2008). Second, it partially contradicts Dienes *et al*.'s (1991) proposal that implicit and explicit knowledge share a common base. If that is the case then, it would be more likely that children with developmental dyslexia would capitalize on the explicit knowledge they acquired during training phase to perform well on the grammaticality judgment phase. However, no safe conclusions can be drawn; instead, these hypotheses should be subject to future research.

## 6.7 Summary

In the present Study 2, children with developmental dyslexia were found impaired in their implicit learning abilities as manifested in a variant AGL task that controlled for implicit and explicit learning processes (i.e. working memory) separately. The implicit learning deficit children with developmental dyslexia show is present even when explicit learning (PFR) is intact. Adding to the tentative conclusions Study 1 reached, the data from Study

2 suggest more strongly that the implicit learning deficit may be specific in nature; children with dyslexia may face problems in abstracting higher-order knowledge that result in poor implicit learning performance.

Taking into account the research that has been conducted in young adult populations with developmental dyslexia using other implicit learning paradigms (see Chapter 4 review), a very interesting picture emerges. Individuals with developmental dyslexia are consistently found impaired in their implicit learning (Bennett *et al*., 2008; Howard *et al*., 2006; Pavlidou *et al*., 2009a; Vicari *et al*., 2005) when the complexity of the learning condition is increased and irrespective of the implicit task in use. Complexity in implicit learning literature is closely related to the notion of abstraction (see Chapter 3, sections 3 & 6) in the sense that when the learning condition is highly complex then abstraction mechanisms are thought to be elicited to help the learner acquire all the relevant information.

In turn, abstraction is almost identified with rule-learning (Dulany *et al*., 1984, 1985; Reber, 1969; Manza & Reber, 1994) and is tested in the AGL context under transfer experimental conditions (Altmann *et al.*, 1995; Gomez & Gerken, 1999) (see p. 68). In the following Chapter 7, the thesis employs a transfer experiment to establish more firmly the possibility this consistent (Studies 1 & 2) implicit learning deficit in children with developmental dyslexia stemming from the inability to abstracting rule-like information.

# CHAPTER 7

# STUDY 3[13]: DOES POOR IMPLICIT LEARNING PERFOMANCE OF CHILDREN WITH DEVELOPMENTAL DYSLEXIA REFLECT AN IMPLICIT ABSTRACTION DEFICIT? EVIDENCE FROM AN AGL TRANSFER STUDY

## 7.1 Aim of Chapter

Chapter 7 reports and discusses the results from the third study of the thesis. Study 3 examines whether the noted implicit learning deficit children showed in the two previous studies of the thesis (i.e. Studies 1 & 2) is a deficit in abstracting rule-like knowledge. The AGL transfer framework provides the theoretical and empirical grounds for exploring implicit abstraction mechanisms, which result in rule-like knowledge, because transfer phenomena (i.e. the finding that learners can transfer knowledge to stimuli that have different surface characteristics but share the same deep structure)  are closely linked with implicit abstraction  (i.e. the underlying structure of old items can still be transferred to novel items that have different instantiation) and rule-like learning in the AGL tradition (see Whittlesea & Dorken, 1993; Manza & Reber, 1994).

[13] The data from Study 3 has been accepted for an oral presentation and publication in the proceedings of the World Conference in Educational Sciences, Instanbul (4-7 February 2010).

Thus, Study 3 employs two experiments; a non-transfer experiment (Experiment 1) and a transfer experiment (Experiment 2). Experiment 1 is a replication of Study 2 of the thesis whereas Experiment 2 is a transfer experiment in which children are faced with a different set of symbols in the testing phase than the one they were trained on. This design aims to firmly establish implicit learning (augmenting the conclusions in Study 2) in a typical AGL task setting (Experiment 1) so that safer conclusions are made with regard to transfer performance (Experiment 2).

## 7.2 Introduction

To date, the two previous chapters reported the findings from the two studies of the thesis (Studies 1 & 2) that utilized variants of an AGL paradigm with different experimental regimes and drew tentative conclusions on how implicit learning seems to function in typical and developmental dyslexic children. The studies report a consistently poor performance (at chance level) of children with developmental dyslexia across all experiments. In direct contrast, typically developing children met the demands of all the AGL tasks (above chance performance). Moreover, there was a grammaticality effect in AGL performance that was kept constant across all experiments. Given that above chance performance is used as an indicator of implicit learning and grammaticality as an indicator of rule-learning, the aforementioned findings support an implicit learning deficit in children with developmental dyslexia and strongly suggest that this implicit learning deficit is a deficit in abstracting information across the stimuli, which results in rule-like knowledge.

As stated earlier, implicit abstraction (see Chapter 3, section 6) is more thoroughly explored and firmly established in AGL transfer experimental settings (see p. 68) (Altmann *et al*., 1995; Gomez & Schvaneveldt, 1994; Manza & Reber, 1994; Knowlton & Whittlesea & Dorken, 1993; Redington & Chater, 1996). In transfer experiments, participants are tested on whether they can successfully (above chance performance) transfer knowledge from old items to new items when the surface characteristics of the new items have changed. Despite that, participants are found to perform at above chance level showing evidence of transfer. To be able to show transfer, participants need to abstract knowledge (i.e. to encode the inherent regularities) across the old items (Reber, 1990; see also Redington & Chater, 1996; Pothos, 2007, for reviews).

Although the possibility of simple hypotheses for transfer (e.g. the acquisition of fragment knowledge during training and its comparison against test stimuli on the basis of a good fit for grammaticality judgments, Redington & Chater, 1996) cannot be safely excluded, there is evidence that simple explicit/declarative knowledge does not mediate transfer mechanisms (Knowlton & Squire, 1996). Therefore, it is highly plausible that successful transfer entails the induction of abstraction mechanisms (Seger, 1994) and the acquisition/formation of rule-like knowledge (i.e. knowledge of repetitive or alternating patterns) (Gomez, 1997). Thus, the thesis utilizes the transfer tradition as it is highly profitable for the in-depth investigation of the nature of the implicit learning deficit found in children with developmental dyslexia.

### 7.3 The present study

The present study considers whether the diminished performance of children with developmental dyslexia in AGL tasks that Studies 1 and 2 of the thesis report, is related to or is the result of a general difficulty in implicitly abstracting rules. To investigate this, Study 3 uses two experiments. Experiment 1 is a non-transfer experiment and is a replication of Study 2 of the thesis. The replication of Study 2 serves two main purposes. First, it is used as means to establish implicit learning in a non-transfer setting for the new set of children who participate in Study 3; instead of making inferences based on the findings from Study 2, implicit learning is tested anew. Second, it is crucial to measure performance in the non-transfer setting so that it can be compared against performance in the transfer setting.

Experiment 2 is a transfer experiment in which all children are faced with a different set of symbols in the testing phase than the one they were trained on. It follows that if transfer effects can be established for typically developing children, then it can be argued that AGL learning is largely abstract and that children acquire rule-like knowledge that enables them to perform well (above chance performance) even when the surface features of the testing set change. By analogy, poor performance of children with developmental dyslexia will indicate an implicit rule-learning deficit. It is the first time that transfer phenomenon is studied in typically and developmental dyslexic children so, the findings can be used as baseline for future studies.

Performance in Experiments 1 and 2 will be measured and compared against each other (a) for all children and (b) for each group separately. This way, inferences can be drawn about both the learning that took place and the kind of knowledge that is acquired during the two AGL tasks. Differences in performance in the two experiments will lead to different accounts of any potential deficits that can be associated with the theory of developmental dyslexia.

### 7.4 Experiment 1: AGL Non-transfer Experiment (Replication of Study 2)

Experiment 1 is a replication of Study 2 of the thesis. Based on the findings of Study 2 (Pavlidou *et al*., 2009b) three major hypotheses are formed for Experiment 1. First, it is expected that all children will require the same amount of exposure to exemplars (PFR) before they can correctly recall the sequences. Second, it is anticipated that typically developing children will show intact implicit learning reflected in above chance performance. Third, children with developmental dyslexia will show impaired implicit learning as manifested in poor AGL performance.

#### 7.4.1 Method

##### 7.4.1.1 Participants

A new set of 32 primary school children between the ages of nine and twelve were included in the study. The same selection procedures to those in Study 1 and Study 2 (see Chapter 5, section 1 and Chapter 6, section 3) were followed. Half of the children were diagnosed having developmental dyslexia and half were typically developing. All the children were matched in chronological age and classroom so that environmental factors such as different teaching experiences could be controlled for and counterbalanced across the sample.

To obtain a sense of all children's verbal and non-verbal abilities a number of tests was administered. Children's reading and spelling performance was measured using the WORD test (basic reading and spelling components). Digit span (WISC IV), Matrix Reasoning (WASI) and Vocabulary (WASI) subtests were used to measure working memory and general intelligence. Based on the obtained scores, the children that comprised the typically developing group had literacy and cognitive scores within or above the normal range (see Table 7.1; see also Table 6.1). The children included in the developmental dyslexia group on the other hand, had reading and spelling ages at least 2 years below their chronological age and average or above average general cognitive abilities (see Table 7.2; see also Table 6.2). This time, children were not matched for IQ performance, however the children that were chosen to comprise the two experimental groups had average or above average cognitive abilities. Given that Experiment 1 of Study 3 is a replicate of Study 2, the difference in the cognitive profile between the groups will also serve the purpose of testing for IQ influences on implicit learning.

**Table 7.1:** Summary of literacy abilities

| GROUP | N | CA | RA | SA |
|---|---|---|---|---|
| **Dyslexic** | 16 | 10y 3m | 7y 6m | > 6y |
| **Typically developing** | 16 | 10y 3m | 9y 11m | 9y 3m |

NOTE: The values represent means of chronological age, reading age and spelling age.

All children were native speakers of English and had normal or corrected to normal vision; no other concurrent conditions were reported for any of them. None of the children had any previous experience with this type of psychological experiments.

Finally, all children had school and parental consent to participate in the study and they were given the choice to opt out at any time (see Appendix A).

**Table 7.2:** WISC and WORD raw scores

| GROUP | DS | MR | VC | BR | SP |
|---|---|---|---|---|---|
| **Devel. Dyslexic** | 13.19 | 19.38 | 24.38 | 20.31 | 7.94 |
| **Typic. Developing** | 16.13 | 23.19 | 30.81 | 33.56 | 20.13 |
| **P value** | 0.003* | 0.03* | 0.01* | 0.00** | 0.00** |

NOTE: the values represent mean for WISC Digit Span, Matrix Reasoning, and WORD Basic Reading and Spelling.
* $p < 0.05$
** $p < 0.001$

All children were native speakers of English, had normal or corrected to normal vision while no other conditions were reported for any of them. None of the children had experience with this type of psychological experiments before. Finally, all children had school and parental consent to participate in the study and they were given the choice to opt out at any time (see Appendix A).

### 7.4.1.2 Materials

The alternative grammar (Knowlton & Squire, 1996) that was used in Study 3 (see Chapter 6, Fig. 6.2) was also used for Experiment 1. Eight training items and twenty novel testing items were created using the same shape set as in Study 2 (see Appendix G.1). The resulting stimulus set had an equal number of G and NG items. To create the NG items an error was introduced in one place of a G sequence. The G and NG items were matched in chunk strength[14] having an equal number of low chunk strength (LCS) and high chunk strength (HCS) items (see Appendix G. 2).

#### 7.4.1.3 Procedure

Experiment 1 followed the exact same procedure to that in Study 2. In brief, during the training phase children were shown four cards that each had two training sequences printed on it. The cards contained progressively longer sequences of shapes. Each card was presented for 15 seconds and the child was asked to memorize and reproduce the depicted sequences freely (PFR) using the provided printed cards[15] of individual shapes. If the child did not manage to reproduce the sequences on the card accurately with the first attempt, the card was shown for another 15 seconds. This procedure was repeated until the child reproduced correctly the sequences on every card (i.e. four cards in total). The researcher recorded the number of trials each child took to achieve perfect recall.

Before children progressed to the testing phase, they were informed about the rule-governed nature of the stimuli they had just memorized. They were then exposed to novel items using the same set of shapes. This time the items were presented on a portable ACER computer screen. They were asked to decide which of the new presented items followed the same rules as the previously memorized items and which did not conform to these rules (i.e. to make grammaticality judgments) (see Appendix G.3). The stimuli

[14] To remind, chunk strength for each testing item was calculated by dividing the total number of bigrams and trigrams it consisted of, with the number these bigrams and trigrams it had appeared during the training phase.

[15] The use of printed cards instead of electronic ones was selected for the same purposes as in Study 2. It increases the trust in the researcher (Reber, 1967), avoids any motor engagement during the task, and reduces the time of the procedure.

remained on screen until the child provided an answer. The researcher recorded the children's answers on paper format.

Once the training and testing phases were completed the children were asked whether they had noticed a specific pattern in the testing items and on what rules, if any, they had based their selections in the testing phase. The majority of children said that they were guessing. Only 3 children reported of using a strategy but this could not solve the complexity of the task, as this wasn't accurate.

#### 7.4.1.4 Design

Performance on the AGL task was calculated using three different measures: a perfect free recall task (PFR), a grammaticality decision task and post-experimental interviews. In the training phase, the number of trials required for PFR of the training items was calculated separately for each participant. Subsequently, typically developing children's performance was measured in each card and was compared with that of children with developmental dyslexia to investigate differences in the amount of the exposure needed to learn the training items.

In the testing phase, a grammaticality-decision task was administered. The total number of G and NG items correctly identified as G and NG was calculated and compared against chance levels for each group. Then a 2 X 2 X 2 design was employed; participant type (children with developmental dyslexia, typically developing children) X grammaticality (G, NG) X chunk strength (HCS, LCS). Classification performance was measured on the two dependent material variables to examine in detail the influence of the different substring characteristics on grammaticality decisions.

### 7.4.2 Results

To test whether both groups of children required the same degree of exposure to the training items before they have achieved PFR, an independent *t*-test was run comparing the mean number of trials each group needed to learn the training sequences. This revealed that both groups of children required the same amount of exposure to the training items ($t_{(30)} = 1.919$, $p > 0.05$). Similarly to Study 2, paired *t*-tests were computed for the four different cards (For dyslexia group: $M^{*}_{1} = 1$, $M_2 = 2$, $M_3 = 2.19$, $M_4 = 3.19$ and for the typical group: $M_1 = 1$, $M_2 = 1.19$, $M_3 = 2$, $M_4 = 3$) to explore potential differences in performance at different levels of difficulty as the cards had progressively longer items (and thus can be considered more demanding). Only the paired *t*-test for Card 2 revealed significant differences in the amount of trials needed to achieve learning ($t_{(15)} = 4.33$, $p < 0.05$). Children required a similar number of trials to achieve PFR for the three remaining cards (see Figure 7.1).

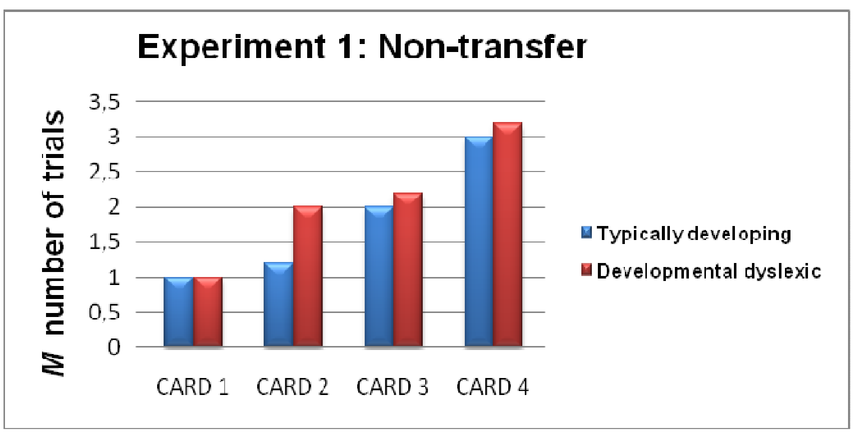


**Figure 7.1** PFR performance for the two groups of children expressed as the mean number of trials required for learning each card.

*The numbers 1, 2, 3, 4 stand for the consecutive order of the cards children were shown.

To explore children's performance during the testing phase of the AGL task single *t*-tests were run for both groups of children comparing children's performance against chance levels (i.e. 0 would be minimum performance, 10 chance performance and 20 maximum). Typically developing children were found to perform at above chance level ($t_{(15)} = 3.530$ $p < 0.05$, $M = 11.75$ SD = 1.98) whereas children with developmental dyslexia were found to perform at chance level ($t_{(15)} = 1.83$ $p > 0.05$, $M = 9.5$ SD = 1.1). Both groups' overall performance is illustrated in Figure 7.2.

Because the two groups of children showed a different learning rate as measured by the *t*-tests, it was decided to further investigate the specific stimulus factors that could have affected the way children responded in the testing phase. To do that repeated-measures ANOVA was run with one factor corresponding to group (dyslexic, typically developing), a second one to grammaticality (G, NG) and a third one to chunk strength (HCS, LCS). Between subjects ANOVA revealed an effect of group ($F_{(1,30)} = 14.46$, $p = 0.001$): There were significant differences in the way the two groups of children performed during the testing phase as independent *t*-tests have indicated. Typical children outperformed children with developmental dyslexia. Within subjects ANOVA did not reveal a main effect of grammaticality or chunk strength however, there was a significant two-way interaction between the two material variables (grammaticality X chunk strength) ($F_{(1,30)} = 7.51$, $p < 0.05$). There was no 3-way interaction.

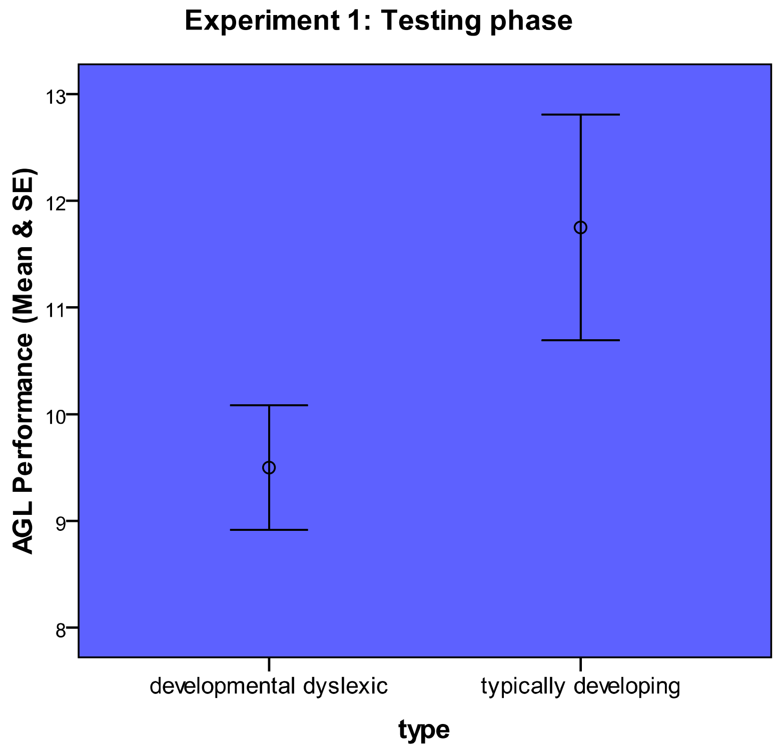


**Figure 7.2** AGL performance expressed as the mean number of correctly identified items during the testing phase.

To assess the source of this interaction between grammaticality and chunk strength paired *t*-tests were employed comparing the performance of children with developmental dyslexia to that of typically developing children in the four aforementioned levels of stimulus characteristics separately (i.e. G items of HCS and LCS, NG of HCS and LCS, HCS both G and NG and LCS items both G and NG). The paired t-test was significant for G items ($t_{(15)} = 3.08$ $p < 0.05$, $M_{1*}$[16] = 4 $SD_1 = 1.63$ and $M_{2*} = 5.56$ $SD_2 = 1.3$) and items of LCS ($t_{(15)} = 2.86$, $p < 0.05$, $M_1 = 4.5$ $SD_1 = 0.95$ and $M_2 = 6.2$ $SD_2 = 1.9$): when the items were grammatical or had low associative strength children with developmental

16 $M_1$ = children with developmental dyslexia & $M_2$ = typically developing children.

dyslexia did not classify them correctly at the same rate as typically developing children. Both groups' classification performance on each substring dependency is depicted in figure 7.3. These findings are consistent with the findings of Study 2.

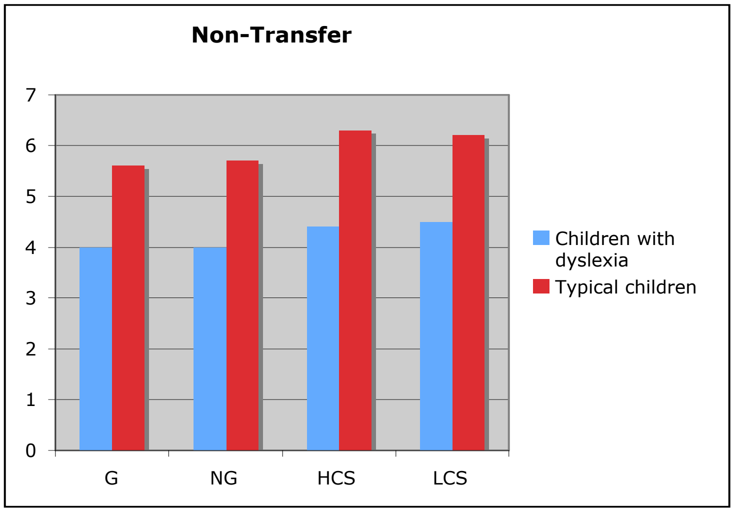


**Figure 7.3** Mean correct classification performance for each substring dependency.

### 7.4.3 Discussion

Experiment 1 was a replication of Study 2 of the thesis. The results from Experiment 1 are in line with the results from Study 2. With regard to the first hypothesis that is whether all children will show the same PFR, all children required similar exposure to memorize the items. Thus, both groups of children seemed to benefit from the structured nature of the items (Pavlidou *et al*., 2009b); the structural regularities facilitated working memory performance equally for both groups.

The results from Experiment 1 verified as well, the second stated hypothesis that typically developing children would show intact implicit learning as in Study 2. Typical children scored at above chance level, which indicates the induction of implicit learning. In direct contrast, children with developmental dyslexia failed to show evidence of implicit learning (chance level classification) and thus, confirmed the third hypothesis: Children with developmental dyslexia were found impaired in their implicit learning performance. Interestingly, there was no overlap in performance of the two groups (see Figure 7.2) that strongly supports clear-cut differences in implicit learning.

In relation to what kind of knowledge children acquired during AGL, the pattern of obtained results highlights and extends the findings from Study 2. More specific, the present findings suggest that both rule-like and fragment-based knowledge (grammaticality and chunk strength interaction) mediate AGL in line with previous findings in adults (Knowlton & Squire, 1996). However, more detailed analysis revealed that fragment-based information was used only for items that were not grammatical. Overall, grammaticality affected classification judgments for typically developing children suggesting that children have used abstraction mechanisms to cope with the demands of the tasks.

The consistency of the current main results with the main results from all previous experiments of the thesis reinforces the hypotheses and conclusions that are drawn for both typically developing and developmental dyslexic children. Children with developmental dyslexia are found impaired in their implicit learning abilities as those tested in an alternative AGL task. Because all the experimental grammars used in the thesis control for similarity (see Vokey & Brooks, 1991), typically developing children's consistently good implicit learning performance (above chance level) is thought to primarily reflect learning of deep structure (i.e. rule learning) (e.g. Manza & Reber, 1994). Thus, the data across all four experiments (i.e. Study 1, Study 2 & Study 3: Experiment 1) strongly suggest that in children with developmental dyslexia while explicit learning mechanisms relating to working memory seem to function at a good level, more abstract mechanisms are impaired and call for further investigation.

However, to argue more safely in favor of an implicit abstraction deficit inhibiting high implicit learning performance of children with developmental dyslexia, abstraction should be established for typically developing children. The following experiment employs a simple transfer setting to explore implicit abstraction mechanisms and rule-like knowledge formation during the AGL task in typically developing children and children with developmental dyslexia.

### 7.5 Experiment 2: AGL Transfer Experiment

In this second experiment, children are given a transfer task, in which the testing items are composed of a different shape set than the one used to create the training set (transfer condition). However, the grammar rules remain the same and thus, two main research questions can be explored by utilizing the transfer tradition in AGL: first, to investigate whether knowledge acquired during the AGL task can be viewed as reflecting abstraction mechanisms, in typically developing children and children with developmental dyslexia. If children show above chance performance in the classification of the novel items then, it can be argued that they transferred knowledge. Given that the surface features of the stimuli have changed some rule-knowledge is mandatory to cope with the demands of the task (Dienes, 1992). Therefore, children need to use abstraction mechanisms as the exclusive information of fragments will not facilitate transfer. Second, the experiment explores the possibility that any failure children with developmental dyslexia show in the task may share a causal link with the way rule abstraction mechanisms function.

It is the first time that a transfer experiment is conducted with children so, no solid predictions can be made. Based on transfer studies in typical adults (see p. 68) that have showed transfer effects despite an overall slightly diminished performance, it is expected that children will show transfer (as manifested in above chance performance). Children with developmental dyslexia on the other hand, show a consistently poor performance on AGL tasks pointing to existing implicit learning problems. Thus, it is very likely that these problems will persist in the current transfer experiment in which good performance requires the abstraction of highly complex rules.

### 7.5.1 Method

#### 7.5.1.1 Participants

Experiment 2 involves the same set of children who completed Experiment 1. To date, all children were matched for chronological age (*M* = 10y 3m, SD = 0y 7m), classroom and gender (18 boys and 14 girls). The same selection procedure (see method section in Chapters 5 & 6) and ethical protocol (see Appendix A) to that of the two previously conducted studies were followed. The criteria for grouping the children were (a) formal school diagnosis of developmental dyslexia and (b) the results from a battery of verbal and nonverbal tests of general intelligence for all children (see Experiment 1, Tables 7.1 & 7.2). Half of the children comprised ‘the typically developing group’ and the rest of the children ‘the developmental dyslexia group’.

### 7.5.1.2 Materials

In the present experiment a new grammar (Knowlton & Squire, 1996; Exp.2, Grammar B) is used to create the training and testing items. Based on the original experimental grammar, eight training items and twenty testing items are constructed (see Appendix H.1). To construct the training items, the grammar's original letters are replaced with geometrical shapes as this: B is replaced with square, L with hexagon, Z with trapezoid and F with diamond (see Appendix H. 1). To construct the testing items, however, the same grammar is used but this time the shapes from the alternative grammar are replaced with another set of shapes as this: Square (B) is replaced with circle, hexagon (L) with rectangle, trapezoid (Z) with triangle and finally, diamond (F) with pentagon (see Figure 7.4). This replacement creates a simple transfer setting.

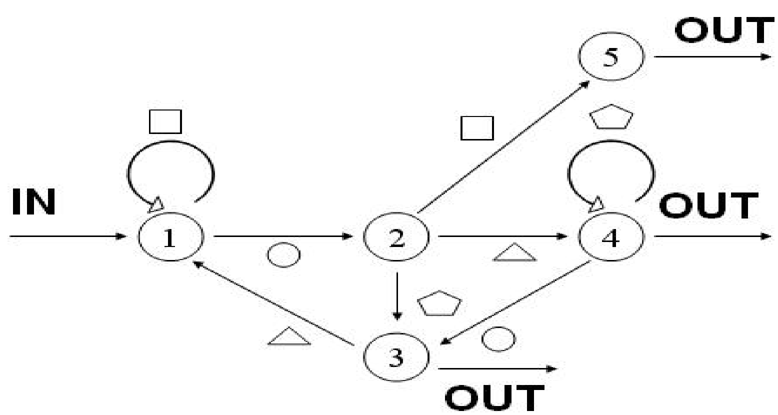


**Figure 7.4** The alternative grammar B (Knowlton & Squire, 1996).

Following Knowlton and Squire's (1996; B) original grammar 10 grammatical (G) and 10 non-grammatical (NG) items were created following the grammar's *IN* and *OUT* arrows. The NG items were constructed by introducing one error in each of the G items. The G and NG items were matched in chunk strength having an equal number of *low* chunk strength (LCS) and *high* chunk strength (HCS) items (half of the items had low and half of them high chunk strength). Chunk strength (see Appendix H.2) for each testing item was calculated by dividing the total number of bigrams and trigrams it consisted of, with the number of times these bigrams and trigrams had appeared during the training phase.

#### 7.5.1.3 Procedure

Experiment 2 was conducted at least one week after Experiment 1 had taken place. A similar procedure was followed to that of Experiment 1. The task was divided into two phases, the training and the testing phase. In the training phase the child was asked to freely reproduce (PFR) a set of eight sequences of geometrical shapes printed on four cards (see Appendix H.1) using the provided printed cards of individual shapes[17] (see Appendix H.3, for the precise instructions children were given). Each card was presented for 15 seconds. This was repeated until the child reproduced correctly all the sequences depicted on each of the four cards; the researcher recorded all trials on paper format.

Immediately after the training phase (PFR), the child was informed about the rule-governed nature of the stimuli she/he had just memorized. Then, the researcher informed the child that the second phase of the experiment would be presented on the computer. The child was told that she/he is going to see new sequences that use a different set of geometrical shapes and has to decide which of the newly presented items follow the same rules with the training items and which do not conform to these rules (see Appendix H. 3). The testing items remained on screen until the child provided a YES or NO answer.

[17] We chose to provide printed cards instead of asking the children to draw the sequences for two main reasons: First, to avoid any motor engagement during the task; second, to reduce the duration of the task as this was administered during school times and in turn, to minimize the amount of fatigue.

The child was encouraged to reply as quickly as possible. The researcher recorded the children's responses on paper format. Once the training and testing phases were completed the child was asked whether she/he had noticed a specific pattern in the testing items and on what rules, if any, she/he had used. All the children said that they were guessing.

#### 7.5.1.4 Design

Experiment 2 adopts the same design as the one of Experiment 1. AGL is measured in terms of the PFR performance in the training phase for each child separately and for each group of children (typically developing and developmental dyslexic) to explore potential group differences in the amount of exposure needed for successful PFR. In the testing phase, the total number of G and NG items correctly identified as G and NG is calculated and compared against chance levels for each group. The experiment has a 2 X 2 X 2 design: group (children with developmental dyslexia, typically developing children) X grammaticality (G, NG) X chunk strength (HCS, LCS). Classification performance is measured on the two dependent material variables.

### 7.5.2 Results

To compare performance on the PFR between typically developing children and children with developmental dyslexia an independent *t*-test was employed. The *t*-test was not significant ($t_{(30)} = 1.3$, $p > 0.05$) indicating that both groups of children needed the same amount of practice to successfully memorize the sequences. The two groups of children exhibited the same learning rate during the training phase replicating this way both the findings from Study 2 and from the current Study 3: Experiment 1. Similar to Study 2 and Study 3: Experiment 1, all children's PFR performance on each card was calculated to test any explicit effects related to card difficulty as the cards had progressively longer training items depicted on them. The paired *t*-tests were not significant for any of the four different cards. PFR for each group of children on each card is shown in figure 7.5 and it is expressed as the mean number of trials.

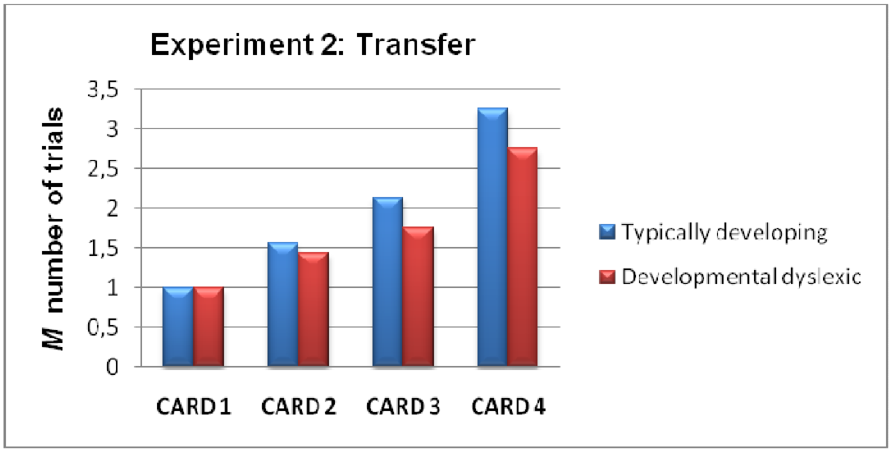


**Figure 7.5** PFR performance for the two groups of children expressed as the mean number of trials required for learning each card.

To examine the learning that took place during the testing phase two different statistical tests were conducted. First, independent *t*-tests were used to assess whether all children's overall classification performance (i.e. the number of G and NG items of both LCS and HCS they were able to identify correctly) was above chance serving as an indicator of grammar learning during the testing phase. In the task chance performance would be 10 (with minimum performance 0 and maximum 20). The *t*-test for the typically developing group was significant ($t_{(15)} = 2.22$, $p < 0.05$, $M = 11.13$ SD = 2.03). In contrast, the t-test for the typically developing group was not significant ($t_{(15)} = 1.15$, $p > 0.05$, $M = 9.06$ SD = 0.81). Only typically developing children identified items at a level that could not be explained by guessing (see Figure 7.6).

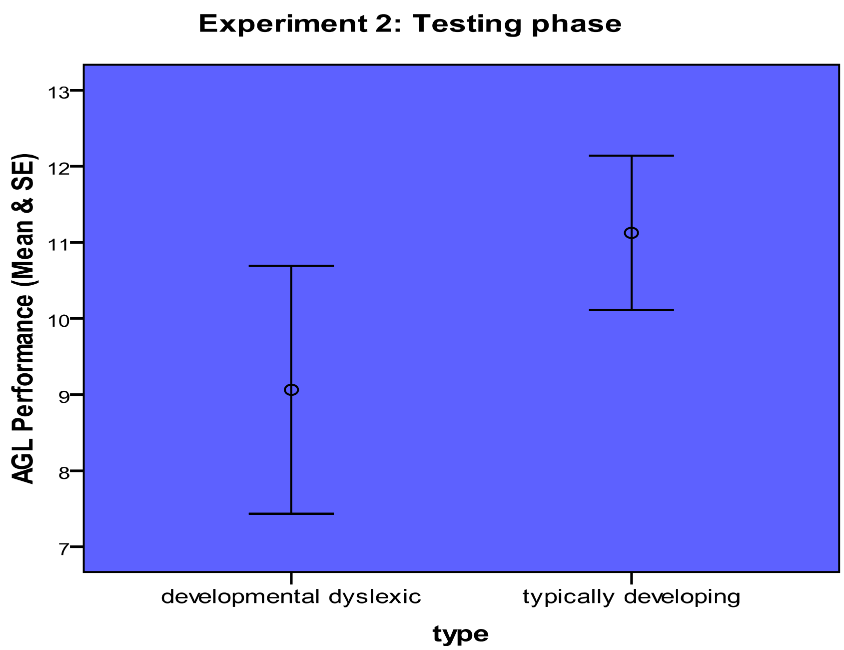


**Figure7.6** AGL performance expressed as the standard error of the mean correct classification judgments.

In line with the analysis done in the previous studies of the thesis, an ANOVA (repeated measures) was used to explore the data more thoroughly. The ANOVA had one factor corresponding to group (typically developing, developmental dyslexic), one to grammaticality (grammatical, non-grammatical) and one to chunk strength (low, high). Between subjects ANOVA showed a group effect ($F_{(1,30)} = 4.63$, $p < 0.05$). Typically developing children outperformed children with developmental dyslexia; this augments the results from the independent *t*-tests.

Within subjects ANOVA showed a main effect of grammaticality ($F_{(1,30)} = 11.32$, $p < 0.05$), a main effect of chunk strength ($F_{(1,30)} = 28.33$, $p < 0.001$) and a two-way interaction of grammaticality X chunk strength ($F_{(1,30)} = 17.07$, $p < 0.001$). There were no 3-way interactions. [As expected, the additional separate independent *t*-tests that were run comparing the two groups performance for each item variable i.e. G, NG, HCS and LCS were all significant]. All substring levels i.e. grammaticality and associative strength affected the way children responded during the testing phase.

However, to explore the particular level of the specific stimulus dependencies at which children with developmental dyslexia showed lower performance, paired *t*-tests were done. The paired *t*-tests compared each group's performance against each other on every specific stimulus dependency separately that is (1) G of both HCS and LCS; (2) NG items of both HCS and LCS; (3) HCS and; (4) LCS items both G and NG (see Figure 7.7). The paired *t*-tests were significant for G items ($t_{(15)} = 3.93$, $p = 0.001$, $M_1 = 3.50$ $SD_1 = 1.37$ and $M_2 = 5.1$ $SD_2 = 1.4$) and LCS items ($t_{(15)} = 3.87$, $p < 0.05$ $M_1 = 3.38$ $SD_1 = 1.63$ and $M_2 = 4.88$ $SD_2 = 1.08$). Typically developing children were able to identify grammatical items (irrespectively of their associative strength) as well as items with low associative strength (irrespectively of their grammatically) at higher rates compared to children with developmental dyslexia. In other words, children with developmental dyslexia had difficulties identifying grammatical items and items that had low associative strength.

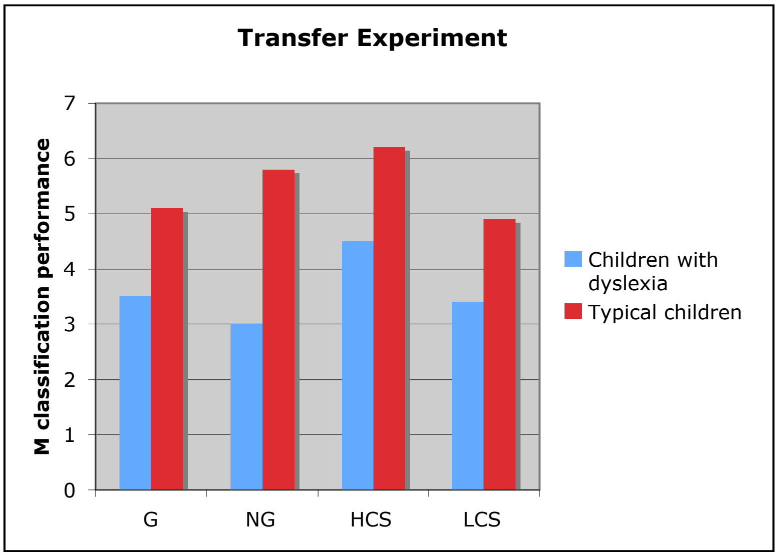


**Figure 7.7** Mean correct classification performance on sub-string dependencies

### 7.5.3 Discussion

The scope of Experiment 2 was to investigate the possibility of abstract learning mechanisms mediating artificial grammar learning in the context of a simple transfer setting. Interestingly, the finding that typically developing children show transfer effects (i.e. they were able to transfer knowledge across the stimuli and recognize new items at levels that cannot be explained only by guessing) provides strong evidence for abstraction processes mediating AGL performance. Typical children's good performance despite the new instantiated shape set constitutes indirect evidence that the knowledge acquired from or mediated by transfer could not be sufficiently explained by mere fragment-based accounts (e.g. Brooks & Vokey, 1991; Whittlesea & Dorken, 1993).

A more detailed analysis of typically developing children's classification judgments during the testing phase revealed that both fragment influences and grammaticality were affecting the way children responded in accord with previous research in adults (e.g. Knowlton & Squire, 1996). Typically developing children were able to recognize correct items irrespective of their substring characteristics. But, because the surface characteristics of the testing items were changed (i.e. different shape set from the one used for training), the fragment-based influences the analysis revealed suggest that children may be sensitive towards repetitive shape combinations instead of specific items. The possibility that children's performance in the present transfer setting reflects the use of 'analogy strategies' (Brooks & Vokey, 1991; Redington & Chater, 1996) is minimized; the transfer setting reduces the amount of readily available information (Lotz & Kinder, 2006). Other predictors of performance however, could explain this sensitivity such as anchor chunk strength[18] or edit distance[19] (Lotz & Kinder, 2006). But since these predictors have not been experimentally controlled are subject to future research.

Nevertheless, fragment-based knowledge (which might be explicit to some extent e.g. children could have mapped the bigram *square-rectangle* that has been identified in the training phase with the bigram *circle-pentagon* of the testing phase) does not provide a satisfactory account of the knowledge children acquire during AGL (see Chapter 3, section 6). Also, the exclusive knowledge of fragments does not explain satisfactorily the transfer phenomenon. Abstract rule learning explanations sit more comfortably in the pattern of obtained results. The performance of children with developmental dyslexia further attests to the possibility that abstract rule-like learning is critical for successful AGL. In spite of their tendency to recognize items of high associative strength, which

[18] It is the number of overlapping initial and final bigrams and trigrams for training and testing items (Knowlton & Squire, 1994).
[19] It is the number of different positions a testing item has compared to its closest in similarity training item (Pothos & Bailey, 2000).

points to fragment influences, children with developmental dyslexia failed to correctly classify items at above chance level. In line with previous AGL experiments, (Chapters 5 & 6; Pavlidou *et al*., 2009a; Pavlidou *et al*., accepted) children with developmental dyslexia show an implicit learning deficit irrespective of the particular characteristics of the learning setting.

The transfer effect established for typical children show that mechanisms for abstracting deep structure are induced during AGL and therefore, any failure to cope with the task indicates abstraction problems. In the light of the transfer effect that was established for the typically developing children, Experiment 2 argues that children with developmental dyslexia face an abstract rule-learning deficit.

### 7.6 Comparison(s) between Experiment 1 and Experiment 2

It was of interest to see whether the two groups performed consistently under the two different experimental settings so that transfer effects can be more firmly established. The two experiments differ in the way the testing stimuli were constructed. To remind, Experiment 1, utilized the same shape set to create both the training and the testing stimuli following the rules of the grammar that was used; it was a non-transfer experiment. Experiment 2, on the other hand, utilized a different shape set to that of the training items to construct the testing items, following however, the same rules of the grammar that was used to create the training stimuli; it was a simple transfer experiment. To compare the overall performance of the two groups in the two experiments that took place a two-way ANOVA was employed examining group (typically developing, developmental dyslexics) X experiment (experiment 1, experiment 2).

### 7.6.1 Results

The ANOVA revealed a main effect of group ($F_{(1, 60)} = 14.99$, $p < 0.001$). However, there was no two-way interaction. Typical children outperformed children with developmental dyslexia in both experiments. The difference in performance was kept constant across experiments; all the children exhibited the same AGL performance irrespectively of the experimental setting (i.e. children with developmental dyslexia performed more poorly compared to typically developing children under both experimental settings).

### 7.6.2 Discussion

Typically developing children and children with developmental dyslexia are found to have differences in the way they respond in the AGL testing performance. This does not come as a surprise if we take into consideration the results from the *t*-tests and the repeated measures ANOVAs that were run for each experiment. Typically developing children perform better than children with developmental dyslexia when more implicit measures of grammaticality are used showing evidence of overall intact implicit learning processes.

Of interest, the differences in the experimental regime adopted in each experiment (i.e. typical experimental procedure and simple transfer procedure) do not seem to affect the way children perform. If children exhibited better performance in Experiment 1 (same symbol set) where knowledge of fragments is more encouraged, one could argue that fragment-based knowledge is primarily mediating implicit learning (Knowlton & Squire, 1996). However, the fact that children showed the same performance under both experiments suggests that abstraction mechanisms mediate primarily implicit learning performance in AGL.

### 7.7 General Discussion

Two experiments were conducted to investigate implicit abstract learning using a non-transfer and a transfer AGL experiments in typically developing children and children with developmental dyslexia. The two experiments served different purposes and added significant data towards the understanding of implicit learning abilities in childhood as those manifested in AGL. Experiment 1 was a replication of Study 2 of the thesis and explored implicit learning in children anew. Experiment 2 examined abstraction during AGL by utilizing the transfer tradition.

Experiment 1 replicated the main results from Study 2 and confirmed the tentative conclusions reached in relation to implicit learning abilities in typical and development dyslexic children. Specifically, Experiment 1 verified that (a) implicit learning is intact in typical children; (b) implicit learning is impaired in children with developmental dyslexia; (c) during AGL both fragment–based and rule-like knowledge is formed. The sensitivity of the children to fragment-based information (i.e. the associative chunk strength) is in line with the view that chunk knowledge can partially explain AGL performance (e.g. Dulany *et al*., 1984; Perruchet & Pacteau, 1990). Yet, despite the fact that all children showed sensitivity to bigram information (chuck strength effect) only typically developing children had an above chance performance. It can be argued therefore, that the exclusive knowledge of bigrams and trigrams is not enough for successful classification of grammatical and non-grammatical items. In the light of such argument, Experiment 2 examined whether AGL performance can be more satisfactorily explained by the abstraction of rule-like knowledge.

Experiment 2 is the first transfer experiment run in children with and without developmental dyslexia. The established transfer effect for typically developing children paired with the grammaticality effect (that denotes sensitivity to the grammatical structure) strongly suggests that abstract rule-like knowledge is largely mediating AGL. Although it is still debatable (Marcus *et al*., 1999; McClelland & Plaut, 1999) whether abstraction in AGL could be explained by the formation of rule-like knowledge or not, our results support the view that AGL performance is largely based on the application view of abstract rule-like knowledge (Marcus *et al*., 1999). By the same token, the salience of abstraction and consequently, of rule learning in AGL explains why children with developmental dyslexia fail to show implicit learning and transfer of knowledge even when they have acquired some kind of fragment-based knowledge during training. The difficulty children with developmental dyslexia show in abstracting knowledge across the stimuli prevents them from meeting the demands of the tasks.

Taken together, the experiments show that (a) typically developing children have intact implicit learning as reflected in good AGL performance; (b) children with developmental dyslexia have impaired implicit learning and; (c) most importantly, the implicit learning deficit is a specific deficit in abstracting rule-like information across complex stimuli. The findings from the transfer study coupled with the findings from the previous studies of the thesis explain the noted difficulty children with developmental dyslexia face in highly complex learning situations as those tested in AGL.

Chapter 7 reported and discussed the first set of data on implicit abstraction in typical and developmental dyslexic children. In general, the methodology adopted in this final study of including a transfer setting and comparing performance against a typical non-transfer learning setting was both useful and revealing; a fuller description of how typical and developmental dyslexic children's implicit learning abilities function was obtained. As well as adding to the extremely limited literature on implicit learning in children, highlighted in Chapter 4, these methods may also provide a means of gaining information on more sophisticated aspects of implicit learning (such as abstraction mechanisms) in typically developing and developmental dyslexic children.

The final chapter of this thesis, Chapter 8, draws together the results of empirical Studies 1, 2 and 3 (reported in Chapters 5, 6 & 7) in an attempt to:

(a) form a more complete picture of how implicit learning abilities develop in typical and atypical children populations;

(b) summarize the potential sources of implicit learning difficulties in children with developmental dyslexia;

(c) discuss how future research could further our understanding on implicit learning in typical and atypical childhood and;

(d) present the educational implications of the findings of the thesis.

# CHAPTER 8

# GENERAL DISCUSSION: REFLECTING UPON THE THESIS

## 8.1 Aims of the chapter

Utilizing the research tradition from the field of AGL, the aim of the thesis was to show how particular implicit learning abilities underpin developmental dyslexic and typical performance. The empirical work in this thesis followed a comparison design, which compared implicit learning performance of children with developmental dyslexia against implicit learning performance of typically developing children. This approach was taken following two basic assumptions; (a) that development could be better understood by studying both typical and atypical populations (Cicchetti, 1984) and; (b) that an implicit learning deficit in children with developmental dyslexia serves as an indicator of possible close links between reading disability and implicit learning. Poor performance of language-impaired populations such as children with developmental dyslexia in non-linguistic tasks, specifically implicit learning tasks, indicates close links between the aforementioned cognitive processes (see also Conway & Pisoni, 2008).

This chapter draws together the results from the five connected experiments presented in the thesis. However, this chapter will not reiterate the discussions presented in previous chapters. Instead, it will focus on synthesizing the main findings and these will be integrated and examined with respect to theoretical issues in developmental dyslexia and implicit learning. This chapter will also consider the possible reasons why children with developmental dyslexia show an inferior ability to implicitly abstract information compared to their non-dyslexic peers. Finally, the educational impact of the present findings will be evaluated in relation to traditional and non-traditional approaches to teaching how to read in typical and developmental dyslexic children.

## 8.2 Theoretical implications

### 8.2.1 Evidence for intact implicit learning in typically developing children

The thesis examined implicit learning abilities in typically developing children and children with developmental dyslexia using the AGL paradigm on the basis of (a) potential developmental differences existing between the two groups of children, which, in turn, can account for differences in implicit learning performance and; (b) the alternative implicit learning processes AGL calls for. Because the thesis has employed a group comparison design, it has produced very interesting findings with regard to implicit learning abilities both in children with developmental dyslexia and typically developing children. Implicit learning has been scarcely studied in typical childhood. The relevant studies have almost exclusively focused on age (Clohessy *et al*., 2001; Thomas & Nelson, 2001) and IQ influences (Fletcher *et al*., 2000; Maybery *et al*., 1995) on implicit learning (see Chapter 3) rather than on implicit learning processes *per se*. For that reason, the experimental work of the present thesis adds important evidence not only in the discussion over the way implicit learning abilities develop in typical childhood but also, in the discussion over the nature of those abilities as marked in AGL. The thesis benefited from the in-built regularities of the AGL (i.e. the grammatical structure and associative strength of the items) that provide the experimental ground to test different hypotheses concerning the above issues.

Children showed a highly consistent good AGL performance (i.e. above chance correct grammaticality decisions) across all five experiments that is a marker of intact implicit learning. Because the children are not explicit taught about the way the stimuli are created they cannot use hypothesis testing; yet during grammaticality judgments they opt for correct items at levels that cannot be explained by mere guessing. Thus, their performance constitutes learning that is largely implicit. This finding concurs with data from previous studies in children and adults that support intact implicit learning in typical development. But what kind of implicit learning takes place? And what is the form of the acquired knowledge?

Because AGL is based on probabilistic learning (i.e. the learning of higher-order dependencies), the learner needs to abstract the regularities across the stimuli (Dienes, 1992) in order to perform well. Thus, deterministic learning (i.e. the learning of first-order dependencies) does not account for above chance performance, as it is not sufficient for the successful completion of AGL tasks; it cannot satisfactorily explain good performance with stimuli of such increased complexity. The sensitivity children show towards the grammatical structure of the stimuli shows that they learn more than simple first-order dependencies: the constant grammaticality effect found in all three studies of the thesis attests to the fact that higher-order learning is taking place during AGL and thus, typically developing children show intact implicit higher-order learning.

In terms of the kind of knowledge typical children base their good classification judgments on, the thesis showed that children acquire both fragment-based (Studies 2 & 3) and rule-like knowledge (Studies 1, 2 & 3), which in turn, can be transferred to new learning settings (Study 3). The transfer effect that was established adds new data in the literature on the nature of implicit knowledge that is either abstract (Reber & Lewis, 1977) or fragment-based (Perruchet & Pacteau, 1990, 1991). Transfer strongly indicates that abstraction mechanisms are engaged in AGL and that the resulting knowledge is in principal (but maybe not exclusively) in the form of rules. Rule-like knowledge explains why children perform well (above chance performance) even when the surface features of the stimuli change. Thus, this thesis argues that typical children acquire knowledge of deep structure, which may co-exist with knowledge of fragments (Redington & Chater, 1996; Shanks & St.John, 1994) and thus, they can transfer this knowledge successfully into other learning settings.

Simultaneously, the finding of the thesis that associative strength contrary to grammaticality is not consistently found to affect classification decisions has two major theoretical implications. First, the sensitivity children show to grammatical structure (grammaticality effect) together with their ability to apply this knowledge of deep structure to stimuli of different physical instantiation (transfer effect) shows that learning is largely abstract (see p. 68 & Chapter 3, section 6). Second, the finding that fragment-based effects (chunk-strength effect) are not kept steady across the studies of the thesis provides support to the hypothesis that higher-order knowledge acquisition (such as rule learning) could be acquired with only the passive exposure to training items and without the build-up from lower level (individual shapes) to mid level (bigrams and trigrams) knowledge. Whether this finding reflects effects from unpredicted/hidden variables or it is the result of the experimental regime adopted, is subject to future research.

Interestingly, the finding that typical children exhibit AGL performance at the lower expected level (i.e. 55 % accuracy; performance varies usually between 55%-65% accuracy) compared to adult performance indirectly illustrates that implicit rule-learning is subject to age influences. As discussed in Chapter 3, the literature suggests that although implicit rule learning is present from infancy (Marcus *et al*., 1999), in childhood the efficiency of implicit learning abilities shows a subtle variance according to age and intellectual level (i.e. older children and more intellectually advanced children tend to do better) (but see also Reber *et al*., 1991). The fact that the typical group was comprised mostly of ten year-old children who had average intellectual abilities (see Tables 6.1, 6.2, 7.1 & 7.2) could explain the reduced performance. Adding an adult comparison group would allow stronger and safer conclusions for this hypothesis. Nevertheless, the data of the thesis coupled with the data from previously conducted studies in different age groups suggests that implicit abstraction mechanisms responsible for the formation of rule-like knowledge are intact in typically developing children. Yet, these mechanisms may follow a maturation process during childhood that reaches its full potential in early adulthood; the mechanisms are kept stable from then on.

To sum up and bring to a close, the thesis suggests that implicit learning as manifested in AGL in typical childhood is (a) intact and; (b) it is better understood as learning of abstract rule-like information. This abstract implicit rule learning that is readily available from infancy allows children to transfer knowledge across different learning conditions. But it may be subject to subtle age and general intelligence differences. Overall, implicit learning of abstract information is well functioning in typical childhood and seems to be fully established (and stabilized) in adulthood.

### 8.2.2 Evidence for implicit learning deficits in developmental dyslexia

Chapter 2 of the thesis set the three empirical studies of this thesis in a research context by describing the need to study developmental dyslexia in relation to contemporary research on learning processes. Developmental dyslexia is primarily studied as a reading disability and different specific causal explanations try to encapsulate the diverse dyslexic phenomena associated with reading. This thesis presents the first set of studies in which implicit learning processes were examined in children with developmental dyslexia using the AGL paradigm.

The most prominent finding of the thesis is the consistently poor performance of children with developmental dyslexia in grammaticality decisions across all five experiments (performance at chance level). This finding was robust even in cases where good explicit abilities such as working memory were established (Studies 2 & 3). Based on the interpretations of AGL performance for typically developing children (unpacked in the previous section), the thesis argues that children with developmental dyslexia are impaired in their implicit learning abilities even if explicit abilities are well functioning (see also Vicari et *al*., 2003). Despite their ability to encode and recall a study item from memory (see good PFR performance in Studies 2 & 3) they cannot extract its regularities (see also Conway & Pisoni, 2008). In other words, children with developmental dyslexia are able to form fragment-based knowledge (as manifested in good PRF performance in Studies 2 & 3) but they do not benefit from this knowledge to learn deep structure (Forkstam *et al*., 2006; Meulemans & Van der Linden, 1997). Given that rule learning is proved to primarily mediate AGL in typical children, the present thesis argues that children with developmental dyslexia are impaired in their implicit rule learning.

The last study of the thesis explored if abstract mechanisms mediate AGL and thus, the possibility that the difficulty children with developmental dyslexia show in implicit higher-order learning (i.e. rule-like learning) stems from a deficit in abstracting rule-like information. In the light of a transfer effect established for the typically developing the difficulty children with developmental dyslexia show in implicit higher-order learning (across all three studies) irrespective of the sub-characteristics of the learning items (i.e. their local regularities or structure abstraction, Folia et *al*., 2008) indicates a deficit in implicit abstract rule-learning.

Overall, the empirical evidence of the thesis suggests that children with developmental dyslexia do not suffer from a general implicit learning deficit (Vicari *et al*., 2005; Vicari *et al*., 2003). Instead, children show evidence of a specific deficit in abstracting highly complex rule information (i.e. abstracting higher-order nonadjacent dependencies, Howard *et al*., 2006). In other words, children with developmental dyslexia face problems in probabilistic learning that hinder the abstraction of the statistical properties in a highly complex learning setting; reading being an analogy of such complex learning setting where the abstraction of regularities plays important role in achieving fluency (e.g. Sperling *et al*., 2004).

To summarize and conclude, the results from all three studies of the thesis reinforce the tentative conclusions reached by the comprehensive review (Chapter 4) of the limited number of studies in developmental dyslexia and implicit learning. The thesis reinforces that implicit learning deficits in developmental dyslexia (a) are not related to the implicit learning paradigm in use (either SRTT or AGL) but rather to the level of the sequential complexity of the implicit task; (b) can still be present even in the face of intact explicit abilities and; (c) do not seem to be associated with factors such as the general cognitive profile of the children.

Most importantly, however, the thesis extends the previous findings by showing that children with developmental dyslexia show a specific implicit learning deficit in abstracting rule-like knowledge (see Bennett *et al*., 2008; Howard *et al*. 2006 for similar findings in adults). If we consider the findings from the literature that indicate intact basic sequential learning abilities in children with developmental dyslexia (see Chapter 4), it becomes evident that while simple associative mechanisms function adequately in dyslexic populations, more sophisticated abstract mechanisms are impaired.

But why do children with developmental dyslexia fail to show implicit learning of abstract, higher-order knowledge? And how does this implicit learning deficit have a role in the etiology of developmental dyslexia? One of the reasons children with developmental dyslexia fail in tasks of advanced complexity could lie in the brain areas associated with such implicit learning tasks such as the fronto-striatal-cerebellar circuits (e.g. Forkstam *et al*., 2006). As stated in Chapters 3 and 4, neuroimaging (e.g. Meghini, Hagberg, Caltagirone, Petrosini & Vicari, 2006; Nicolson & Fawcett, 1999; Nicolson, Fawcett & Dean, 2001) and behavioral data (e.g. Howard *et al*., 2006) associate implicit learning (i.e. higher-order sequential learning) with fronto-striatal-cerebellar brain areas and in turn, specific implicit learning deficits with low-level activation in these areas. This association stems from the assumption that the acquisition and automatization of new skills such as reading relies on these neural circuits. At this point, it is necessary to clarify that although implicit learning is thought to be automatic (i.e. requires the minimum attentional resources, see Chapter 3, section 2), automatization does not always overlap with implicit learning; new skills can also become automatic after repetitive training (Folia *et al*., 2008).

Nevertheless, implicit learning is tightly linked with automatic learning mechanisms responsible for the extraction of regularities across statistical and probabilistic sequences (Conway & Pisoni, 2008). Nicolson and Fawcett (1990) suggest that individuals with developmental dyslexia have problems with automatization of any new skill because of underlying cerebellar deficits (i.e. abnormal cerebellar activity) (Nicolson & Fawcett, 1999; Nicolson, Fawcett & Dean, 2001) that result in problems with higher levels of processing (Moores, Nicolson & Fawcett, 2003). Hence, it is plausible that implicit learning and automatization share common cognitive links and a combined deficit could account for the inability to master reading fluency in developmental dyslexia.

### 8.2.3 Does AGL enhance our understanding of implicit learning? Implications for implicit learning theory.

As stressed in Chapter 5, the choice of the AGL paradigm to be the experimental paradigm for this thesis was made on the basis of a number of different reasons; ranging from inbuilt characteristics of AGL tasks to the learning/cognitive processes AGL taps into (see section 5.2). Most importantly, AGL can take up a more pure implicit form compared to serial reaction time tasks given the complexity of its rule system. The different cognitive processes, on which performance relies, can also be broken down experimentally so that explicit influences can be separately computed and examined. But is AGL really an implicit learning task? If so, can the use of this paradigm further our understanding of how implicit learning functions in childhood? Overall, the results from the present thesis suggest that AGL induces implicit learning but most importantly, that it taps into different aspects of implicit learning, so it should be further employed in the exploration of implicit learning in childhood.

More specifically, with respect to whether AGL induces implicit learning, the reported results provide strong evidence that the high-level complexity of the rule system governing the stimulus set largely calls on implicit processes. Implicit learning was consistently demonstrated across the five experiments for the typically developing group, in spite of performance being at the lower expected level. The transfer effect that was established in the fifth experiment adds weight to the argument that the AGL induces abstraction mechanism that result in rule-like knowledge. As stated in Chapter 3 (section 6) transfer phenomena (e.g. Manza & Reber, 1994; Whittlesea & Dorken, 1993) have been closely linked with abstraction mechanisms (e.g. Lotz & Kinder, 2006; Redington & Chater, 1996) and in turn, with rule learning. However, given that in most real-life learning situations there is a blend of both types of learning, explicit influences cannot be firmly excluded (e.g. Manza & Reber, 1994; Perruchet & Pacteau, 1990). Nevertheless, the ability to transfer knowledge from one learning condition to a different condition strongly indicates that the learner uses abstraction mechanism during AGL; AGL examines implicit abstraction mechanisms and therefore, its use is highly advantageous in exploring implicit abstract learning.

The ability to break down and measure AGL performance provides us with means to examine different factors that affect implicit abstract performance. As stated earlier, typically developing children acquire knowledge of both local substring dependencies (e.g. Perruchet & Pacteau, 1990; Shanks & St.Johns, 1994) as well as long-distance dependencies, possibly in the form of rules (e.g. Dulany *et al.*, 1984; Reber, 1967). It is also very likely that typically developing children use the acquired 'local knowledge' to make grammaticality judgments (e.g. Forkstam *et al.*, 2006). Looked at together, the findings of the current thesis provide support for the possibility that dual-mechanisms mediate AGL, an idea that is supported by Knowlton and Squire's work (1994, 1996) on amnesic patients. The thesis supports the existence of dual learning mechanisms mediating AGL performance by showing that both fragment-based (chunk strength effect) and rule-like knowledge (grammaticality effect) is formed. However, the constant sensitivity that typical children show towards the grammatical structure of the items and the transfer of knowledge to new items suggests that children acquire more knowledge than just knowledge of fragments. Thus, the thesis suggests that children are primarily learning knowledge that is the form of rules.

In addition, the thesis showed that children with developmental dyslexia are found spared in the explicit learning of training items but impaired in the implicit abstraction of the regularities amongst these items. At a theoretical level, the dissociation between implicit and explicit learning during AGL provides additional evidence for the explicit/implicit learning systems debate (see also Green & Shanks, 1993). The findings suggest that independent learning systems may exist. These systems can operate in parallel or interact depending on the nature of the task and the cognitive demands it poses on children.

Also, of note is the fact that typically developing children show implicit learning when sequences of shapes are used and they are able to transfer their knowledge to a new shape set. This adds evidence in support of the domain-general view of implicit learning (e.g. Pothos & Bailey, 2000) as opposed to the domain specific view of implicit learning (e.g. Conway & Christiansen, 2006, 2005). Current research data reported in Chapter 3 (section 5) suggest that implicit learning calls on different cognitive and brain structures varying in the degree of activation depending on the type of the task (i.e. the structure of the task and cognitive demands it imposes on the participants). Theoretically, the use of shapes (instead of the usual letter set) makes the alternative AGL of the thesis non-linguistic, which further support the amodal view of implicit learning. Yet, the likelihood of children using verbal encoding strategies (Conway & Pisoni, 2008) cannot be firmly excluded because the names of the shapes were familiar to the children; some children might have used verbal strategies to meet the demands of the tasks. Recent studies (e.g. Conway, Karpicke & Pisoni, 2007) suggest that typically developing individuals can learn implicitly complex sequential patterns especially when these can be represented phonologically (Conway & Pisoni, 2008). Whether the implicit learning deficit reported here can be interpreted instead as a specific implicit phonological deficit requires further investigation.

To summarize, AGL is largely an implicit learning paradigm that calls on abstraction mechanisms, which result in knowledge that is primarily in the form of rules; the formation of rule-like knowledge may co-exist with fragment knowledge to facilitate performance. Thus, research into implicit abstract learning in childhood can benefit greatly from the employment of this research tool, which can put under test different hypotheses regarding those processes.

### 8.3 Educational implications

As stated in Chapter 2, developmental dyslexia is technically classified as a learning disorder (APA, 2000), which is mainly characterized by poor reading performance. Reading is primarily acquired through explicit learning for example, the acquisition of good phonological abilities. However, there are suggestions (e.g. Combert, 2003; Sperling *et al*., 2004) that fluent reading is achieved with the presence of other pre-reading (and concurrent) skills such as implicit learning. This thesis provides consistent and robust evidence of intact implicit learning abilities in typically developing children but impaired implicit learning abilities in children with developmental dyslexia (Chapters 5, 6 & 7). It follows that teaching approaches could capitalize on the good functional implicit learning abilities of typically developing children and target the underlying implicit learning deficits of children with developmental dyslexia (Bennett *et al*., 2008) to maximize learning outcomes in the classroom.

In the school context, the kind of learning that takes place is primarily explicit, that is intentional and supervised (Folia *et al*., 2008), as opposed to the unintentional and self-organized learning (e.g. Petersson, 2005) that takes places (concurrently with explicit) in everyday life. Traditional strategies for teaching how to read usually employ explicit teaching methods (e.g. the teaching of individual letters or of grammatical rules). Incidental and informal teaching strategies (e.g. whole language strategies) are rarely used in the classroom because for the majority of educators complex information can be primarily conveyed using explicit learning approaches (see Reid, 2003 for a wide range of teacher's practices for reading and spelling instruction). Although, explicit learning is thought to be more workable in simpler learning settings (Green & Hecht, 1992), it is not always equivalent to successful acquisition when other factors such as the complexity of the instructions are in play (McWhinney, 1997). The complexity of the learning setting and the instructional rules may lead to poor explicit learning hindering children from reaching their utmost learning potential. The data from the current thesis illustrate the importance of implicit learning processes in coping with highly complex learning settings (Reber, 1967). As a result, the teaching methods applied in school populations with and without developmental dyslexia could be moderated in such a way as to incorporate the present findings.

To begin with, the data presented in the current thesis are in accord with the natural versus formal learning data suggesting that children with developmental dyslexia will not benefit greatly from incidental learning conditions. The findings from the literature on the effectiveness of natural learning as opposed to formal learning in spelling performance (Graham, 2000) make the educational impact and value of the empirical findings reported in this thesis clear. Children with learning difficulties do not seem to improve their spelling capacities when incidental learning is the primary source of learning (Kerchner & Kistinger, 1984; MacArthur, Graham, Schwartz, & Schafer, 1995). Therefore, naturalistic teaching strategies such as whole language approaches may not be the most suitable for teaching school children with developmental dyslexia.

Moreover, the lack of transfer effect of implicit knowledge (reported in Study 3, Experiment 2) minimizes the possibility of transfer learning effects. For example, any transfer effects from reading to spelling performance (for findings in adults see Ormrod, 1986a, 1986b) and *vice versa* will be rather limited for children with developmental dyslexia as opposed to typically developing children. So, any attempts to transfer the gains from one learning setting to another in children with developmental dyslexia may prove at least difficult. Most importantly, however, children with dyslexia can be explicitly taught to use strategies to compensate for such aforementioned difficulties (Stoodley *et al*., 2008) and become independent readers.

Take an example: if a child with developmental dyslexia has difficulties in implicitly abstracting information (as studies 2 and 3 have shown) when faced with print then in all probabilities, whole word (i.e. incidental teaching) strategies will be of little help for the child to reach fluency. Instead, the child may greatly benefit from the reinforcement of typical teaching strategies such as phonics, which range from direct instruction of simple letter-sound learning to more complex subsyllabic segmentation. Then the child can move on to more complex metacognitive strategy-based learning such as text-reading activities (see Lovett, Lacarenza & Borden, 2000 for an example of a detailed remedial teaching program). This way, the teaching approach will help the child to compensate for impaired implicit learning abilities and achieve her/his full learning potential.

In the case of typically developing children, however, naturalistic teaching approaches can be used to take advantage of the well-functioning implicit learning abilities on the basis of the probabilistic (i.e. higher-order) relationships that characterize the written language units (Conway & Pisoni, 2008). For example, typical children can be taught using whole-word strategies to enhance their literacy skills following the assumption that extensive incidental exposure (which facilitates the emergence of implicit learning processes) helps the development of higher-order mappings in reading (e.g. Combert, 2003) and spelling (e.g. Sperling *et al*., 2004). Yet, it is not implied that explicit learning should be banished but that it can co-exist with implicit learning teaching strategies so that children can have the best of both approaches to learning.

To summarize, the information acquired from the current thesis can be taken into consideration when designing teaching programs for typically developing children as well as intervention schemes for children with developmental dyslexia. In practical terms, the present findings provide us with means of assessing the best way of facilitating the acquisition of complex knowledge (Reber, 1967) maximizing this way the learning outcome.

### 8.4 Limitations and future research

To date, Reber's (1992) account regarding the invariance of age, IQ and psychological or neurological insult in the development of implicit learning abilities had a great influence on empirical research. This could explain the limited empirical data coming in from younger age groups of typical populations but most importantly and relevant to this thesis of atypical populations. In spite of the potential importance of implicit learning abilities for theories of development, empirical support for 'normal' development of implicit learning abilities comes only from three studies in developmentally atypical populations with autism (Mostofsky, Goldberg, Landa, & Denckla, 2000), attention hyperactivity disorder (Thomas, Welsh, Eccard, Livnat, Pierri, & Casey, 1998) and Williams syndrome (Don *et al*., 2003). The finding that implicit learning is intact in such atypical populations led the assumption that implicit learning is “fully fledged” (Fletcher *et al*. 2000, p. 246) from early in development and thus, it is not affected by developmental variance.

This thesis argues against the proposed invariable development of implicit learning by producing the first set of data on children with developmental dyslexia, which points to implicit learning deficits in reading impaired children’s populations. The empirical work in the thesis is a starting point in the study of AGL in developmental dyslexia and can be used as a baseline for similar future studies. However, the thesis highlights the need to be cautious when creating, administering and interpreting the results from implicit learning tasks in children with developmental dyslexia. It is a challenging endeavor given the heterogeneity of children diagnosed with developmental dyslexia and the various diagnostic procedures followed in each given setting.

The thesis adopted a group comparison design that provided important and much-needed evidence on how implicit abstract learning may be related to basic cognitive and literacy abilities. Because the groups were matched in basic cognitive abilities but differed in their basic literacy skills, difference in implicit learning performance is taken to indicate that implicit learning, namely abstract rule-learning, is salient for successful literacy development (i.e. for reading and spelling) but is not related to IQ. However, if we could replicate this with much more tightly matched sample we could draw much stronger conclusions. Future empirical work could explore implicit learning performance as reflected in AGL performance at an individual level of analysis provided very carefully matched sample. Nevertheless, further research into group differences can produce interesting data on how implicit learning functions across development, by contrasting performance in populations with various linguistic and non-linguistic profiles.

It has to be noted at this point that the formation of two experimental groups was based on measuring various basic cognitive abilities so that different hypotheses relating to implicit and explicit learning could be more thoroughly explored. However, given that it is likely to have an overlap between implicit and explicit learning, more explicit measures can be used in future research to test various hypotheses. It would be very interesting, for example, to include tests of attention given that children with dyslexia have been associated with deficits in attention (see Chapter 2). This way, we can theorize more firmly how aspects of explicit learning relate/affect/influence particular implicit learning abilities and how these relate to reading performance. Correlations between such explicit measures and different implicit learning abilities (as those tested by different implicit learning paradigms and their alternatives) can potentially explain more profoundly not only how these types of learning blend in complex learning setting but also why children with dyslexia seem to fail in implicit learning tasks (and in learning tasks such as reading that require a blend of explicit and implicit abilities).

As stated above, the findings from the present thesis, strongly suggest that implicit leaning plays an important role in reading development and partially explains the reading problems children with developmental dyslexia face. The inferences about the relationship between reading and implicit learning could be more thoroughly explored by looking at how task performance and cognitive and literacy scores correlate. The sample size (small) and experimental design (i.e. group comparisons) of the three studies in this thesis did not allow such an exploration (e.g. run regression/correlation analyses) to take place. Future research could focus on specific aspects of reading and how these aspects relate to implicit learning theory. For example, cross-language studies (e.g. Wimmer & Goswami, 1994) suggest that the development of reading skills may differ depending on the nature orthography (i.e. transparent or opaque). The ease of decoding in transparent orthographies (such as Greek) is associated with greater availability of cognitive resources for higher-order processing as opposed to opaque orthographies (such as English) where the availability of these resources is probably lesser (Wimmer, 1993). In the light of such proposition, it would be interesting to investigate how implicit learning performance relates to reading in different orthographies and the longitudinal effects of implicit learning as a potential precursor of fluent reading.

This thesis made use of the AGL paradigm for the first time in children. AGL is more advantageous over other implicit learning paradigms in inducing learning of deep structure, which can be measured and experimentally manipulated. Therefore, the thesis utilized AGL to explore abstract learning and has produced interesting evidence in favor of rule-like knowledge representation during implicit learning. Future studies though, could take into consideration other aspects of AGL that have not been experimentally explored in the current work and can be associated with other aspects of learning in developmental dyslexia. It would be interesting, for instance, to investigate the possibility of specific item effects (e.g. item length) influencing AGL performance that is if and how longer response times may be associated with poor performance for children with developmental dyslexia.

Alternatively, future work can add data to the literature on AGL using different modalities (i.e. auditory and tactile). The finding that performance in typical populations is higher for auditory stimuli (Conway & Christiansen, 2005) than for visual stimuli, could initiate research in implicit learning abilities in developmental dyslexic populations using different input modalities. In the light of such findings and of incoming data suggesting that different learning mechanisms mediate different types of perceptual input (e.g. Goschke, Friederici, Kotz & van Kempen, 2001; Keele, Ivry, Mayr, Hazeltine & Heuer, 2003), it would be interesting to explore specific stimulus effects. For example, implicit learning performance could differ depending on the type of items (e.g. shapes, colors or tones) (multiple view of implicit learning). Developmental dyslexia has been linked with specific perceptual deficits (both in terms of input and output; see Chapter 2, e.g. the magnocellular theory of developmental dyslexia) so, exploring AGL performance in other modalities and using various types of stimuli could reveal other implicit learning processes that are spared or impaired. These implicit learning processes could a have a share in the etiology of dyslexia or indicate ways of enhancing learning in children with developmental dyslexia (e.g. introducing information in the classroom using different means of presentation that cover a range of learning styles, Reid, 2003).

The main finding of this thesis, that is the presence of a true implicit learning deficit affecting reading in children with developmental dyslexia, provides also the ground for future research of implicit learning abilities in bilingual populations with suspicion of having developmental dyslexia. The basic issue in the diagnosis of developmental dyslexia in bilingualism is primarily associated with the identification of true learning difficulties. The long-term use of IQ measures and of phonological batteries for the diagnosis of learning difficulties in bilingual populations seems to underestimate the literacy skills and abilities of the children (Frederickson & Frith, 1998) as well as their cognitive abilities (Cline & Reason, 1993; Cummins, 1989; Ogbu, 1978). The use of such diagnostic practices is based on the widely held view that for successful second language acquisition, overall language proficiency is considered crucial (Geva, 2000).

According to Chall (1996) second language proficiency and reading ability develop in parallel and gradually (i.e. following different stages of development) in contrast to first language acquisition where language proficiency precedes reading ability. However, the study of oral language proficiency and its relationship with reading ability has produced controversial findings (e.g. Durgunoglu, Nagy & Hancin-Bhatt, 1993). Overall, there are many cases where bilingual children show the same reading abilities with monolinguals but face problems with reading comprehension (i.e. semantics and syntax). It is still not clear how semantic, syntactic and phonological abilities function and intersect in bilingual populations as problems in any of these abilities can provide a different causal explanation of a reading disability (Frederickson & Frith, 1998). However, the aforementioned cases indicate that bilingual children may be facing problems with more sophisticated reading-related skills that may not be directly affected by phonology. Hence, shifting the focus away from explicit abilities to implicit learning abilities may elucidate aspects of literacy development in such populations and solve taxonomical issues regarding bilingual populations with reading impairments.

## 8.5 Conclusion

The thesis has provided a much-needed and very important contribution to the very small literature on implicit learning among children with developmental dyslexia and typically developing children and discussed how implicit learning can be of great value in the adoption of appropriate teaching methods for all children. Specifically, the work reported in this thesis has initiated research into specific implicit learning abilities namely, implicit higher-order learning in children with and without developmental dyslexia by presenting the first set of data using the AGL paradigm.

The most prominent finding of the thesis is that children with developmental dyslexia show a deficit in abstracting higher-order information in highly complex learning settings whereas typical children show intact implicit higher-order learning. Reading is an analogy of such complex learning setting where the abstraction of dependencies is crucial for the learner to achieve fluency. It becomes evident that a deficit in the ability to abstract patterns may have a knock-on effect on reading and it can explain the inability of dyslexic readers to master fluent reading even when other reading-related explicit learning abilities (e.g. phonological abilities) are intact. In direct contrast, the intact implicit learning that was established for typical children facilitates reading performance and helps typically developing children to become fluent and independent readers. Given that typical children and children with developmental dyslexia have a different linguistic profile, the data indicate a potential overlap between the cognitive mechanisms of implicit learning and reading. This possibility is also augmented by neuropsychological studies that identify similar areas of neural activation in implicit learning and reading tasks (e.g. Conway & Pisoni, 2008; Forkstam *et al*., 2006). Thus, the thesis argues that implicit learning can offer the ground to test commonalities in some of the cognitive processes engaged in reading (and spelling). Implicit learning abilities may firmly prove to be universal requirements for competent reading and spelling.

The investigation of implicit learning abilities in typical populations has been identified as educationally significant, especially if studied in the early years before formal education. There is no reason why this should not be the case for children being at risk of developmental dyslexia. The screening of implicit learning abilities before children enter formal schooling may facilitate early identification of developmental dyslexia amongst very young populations. The only way however, of testing any possible causal hypotheses between implicit learning processes and literacy skills in developmental dyslexic populations is actually to test these hypotheses in training studies where children receive tailored training or teaching that corresponds to the data on how implicit learning abilities function.

According to Aristotle, he who considers things in their first growth and origin will obtain the clearest view of them. In the light of this, it was the aim of the thesis to study implicit learning abilities in typical and atypical children's populations. Overall, the data clearly argues for an implicit learning deficit in children with developmental dyslexia. This deficit can be partially held responsible for the arduous reading that children with developmental dyslexia exhibit. Likewise, the thesis proposed ways of exploring more hypotheses on how implicit learning abilities relate to specific aspects of the literacy profiles of reading-impaired populations. The importance of the findings of this thesis is primarily reflected in the educational implications that were outlined and which can alter the way children experience learning.

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# APPENDIX A

# CHILDREN AS RESEARCH PARTICIPANTS: ETHICAL ISSUES

## A. 1. Introduction

When conducting research that involves children being the participants, then two issues are at large: informed consent and confidentiality. The British Psychological Society (BPS) constantly updates the Code of Ethics and Conduct (2009) to ensure that high research standards are met for both the participants and the researchers. Both consent and confidentially are essential in all stages of research and hence are also addressed in the current research work.

## A. 2. Informed consent

The aforementioned code affirms that when participants cannot provide an informed consent themselves then the researcher must seek to obtain consent from various safeguards before any actual research takes place. Numerous factors were taken into consideration when choosing the schools that would be approached. The fact that pupils with developmental dyslexia attend mainstream schools made every primary school a potential target for approach; but at the same time there were schools that included a larger number of pupils with developmental dyslexia in their population or had a long history of special interest in and/or effective learning support of children with developmental dyslexia. Additionally, the social differences that are reflected in the "dichotomy" of public/private versus state schools (with a variety of socio-economic backgrounds existing simultaneously in the same school) made it almost mandatory to include a variety of schools in terms of the schooling form and regional district.

Taking all these factors into consideration, several schools were selected and approached by a letter pack for the Head teacher (or/and the learning support teacher alternatively) (see Appendix D) explaining the nature and the aims of the project. Additional requirements (such as space availability or any further clarifications regarding the project) were only considered once the school had given positive response to the request. The next step was to send out parental consent letters (see Appendix E) that briefly explained the basic procedures and the purposes of the study. In keeping with these guidelines, the present research had to be granted formal consent from the parents/guardians of the children who were to participate. But given that all experiments were conducted in a school setting, consent had to be given from a wider number of safeguards; those being the local educational authorities (see Appendix B), the head teachers and learning support teachers, the parents and the children themselves when possible.

Once informed permission was granted from the City of Edinburgh Council and the stakeholders in the primary schools (see Appendix C), parents had in turn, to provide permission for their children to participate in the experiments. To make sure that parents were fully aware of the reasoning behind giving consent for their children's involvement, the researcher had to provide all necessary information about the research itself. This would facilitate parents understanding of how the research might have an effect on the child. To inform parents effectively on such issues a letter was sent stating who the researcher was[20] and explaining the purposes of the research, the entailed processes and the estimated timeframes for its completion (see Appendix D). The letter had an 'opt-in' choice rather than an 'opt-out' choice to discourage parents from feeling obliged to allow their children's participation, especially because the contact was done via the school. The child could start working with the researcher only once consent was obtained. Finally, the children themselves were given the option to opt out at any given time throughout the research.

### A. 3. Confidentiality

In BPS' s 'Ethical Principles for Conducting Research with Human Participants' (2009) code (section 7.1) it is stated that "subject to the requirements of legislation, including the Data Protection Act, information obtained about a participant during an investigation is confidential unless otherwise agreed in advance. (…) Participants in psychological research have a right to expect that information they provide will be treated confidentially and, if published, will not be identifiable as theirs. In the event that confidentiality and/or anonymity cannot be guaranteed, the participant must be warned of this in advance of agreeing to participate" (p. 5).

Consequently, all the data, files, individual and school information were kept secured and were used only to serve the educational purposes of the present academic work while they were rendered anonymous once personal identification was not essential anymore (e.g. schools were described by geographical area and the children's literacy and cognitive profiles were anonymous in all published manuscripts including the

[20] The researcher had undergone disclosure prior to initiating all formal procedures in all level of research.

thesis itself). Confidentiality was mainly serving the purpose of disabling the identification of any particular individual or school.

### A. 4. Comment

The challenges and dilemmas a researcher can be faced with when working with children are not only confined to the issues addressed above but are relevant to the specific research context. However, following the guidelines and baring in mind the rights of the children will ensure the best possible circumstances to conduct research.

### Bibliography

Greig, A., Taylor, J. & MacKay, T. (2007). *Doing Research with Children*. Sage Publications: London.

MacNaughton, G. & Smith, K. (2005). *Transforming research ethics: The choices and challenges of researching with children* (p112-123). In Farrell, A. (Ed.) Ethical Research with Children. Open University Press: Berkshire.

The British Psychological Society. (2009). *Code of Ethics and Conduct*. The British Psychological Society, Leicester.

The British Psychological Society. (2009). *Ethical Principles for Conducting Research with Human Participants.* The British Psychological Society, Leicester.

# APPENDIX B

## THE CITY OF EDINBURGH COUNCIL APPROVAL

Elpida

I am writing further to our most recent meeting, earlier today. Thank you for bringing in your Enhanced Disclosure Scotland clearance, the final piece of paperwork required for administrative purposes.

As discussed, your research request has now been approved by the Schools Service Managers although as you are aware, any final decision to participate will be up to each individual Head Teacher, then their staff, the parents/guardians and the pupils themselves.

I will copy this email to the Head Teachers of each of the schools you are approaching, including the one which has so far given you their approval in principle.

Please keep me up to date with how things are going and get in touch with me if I can be of any further help.

Margaret
Margaret Devenney
Quality Development
Children and Families
Level 2, Wellington Court
Phone: 469 3969
mailto:margaret.devenney@educ.edin.gov.uk
<mailto:margaret.devenney@educ.edin.gov.uk>

# APPENDIX C

# EXAMPLE OF LETTER FOR HEAD TEACHERS

**Date:**

**Re: Children's Learning Study**

Dear sir/madam,

My name is Elpida Pavlidou and I am a second year PhD student at the University of Edinburgh in Moray House School of Education. My supervisors are Dr. Reid (Senior Lecturer) and Dr. Williams (Lecturer). I am conducting a study which aims to explore the implicit learning-that is the automatic and unconscious way of acquiring knowledge- in monolingual pupils with and without dyslexia between the ages of **9-12**.I have already contacted The city of Edinburgh Council, Children and Families Department (I went through Disclosure Scotland) and I gained authorization to proceed with my project.

This study involves the completion of a task performed on a computer screen; its duration is approximately 20-30 minutes and is developed from published research. In brief, the tasks, which are divided into training items and testing items, are sequences of simple white geometric shapes upon a black laptop computer screen, which I will provide for each testing session. Each child will be tested individually and all the information supplied will be **strictly confidential,** according to the University's code of ethics. This research does not measure school knowledge of any kind nor is an assessment/ diagnostic tool.

I am interested in testing any child between the ages of **9-12 monolingual** and **native speakers of English** with formal diagnosis of **dyslexia**. The control group (students between the ages of 9-12 **without dyslexia**) will be formed according to the number of dyslexic monolingual students that will be identified and agreed to participate in my study. All the formal procedures of the University Code will be followed (i.e. parental permission letters). I will not need for than a working week (usually takes less than that) to test all the children.

I have already contacted your learning support teacher and informed her about the procedures involved. I will be happy to answer or discuss in greater detail any questions or concerns you might have regarding the project itself. I thank you in advance for your cooperation. Your help is vital for the continuation of my work.

Yours sincerely,
Elpida Pavlidou

# APPENDIX D

# EXAMPLE OF PARENTAL CONSENT LETTER

**Dear parent**,

**Re: Children's Learning Study**

I am **Elpida Pavlidou**, a second year PhD student at the University of Edinburgh. My supervisors are Dr. Reid (Senior Lecturer) and Dr. Williams (Lecturer). I am conducting a research project which aims to explore the implicit learning- that is the automatic and unconscious way of acquiring knowledge- in children between the ages of 9-12.

The study will involve children being given a task performed on a computer screen, which lasts approximately 20 minutes developed from published research. The tasks are in the form of sequences of simple geometric shapes. The test is divided into two parts; the training phase and; the testing phase. This task does not measure school knowledge of any kind nor is an assessment/ diagnostic tool. Each child will be seen individually. All the information supplied for and by your son/daughter will be **strictly confidential**. Your child has been selected **randomly.**

I hope that you will agree for your child to take part in this study. It is also hoped that this study will provide not only theoretical and statistical data but also useful information for educational authorities.

If you have any questions or concerns about the project itself, the contact details of my supervisors are given below:

| | |
|---|---|
| Dr. Gavin Reid (Senior Lecturer) | Dr. Joanne Williams (Lecturer) |
| Tel: 0131 651 6381 | Tel: 0131 651 6339 |
| E-mail: gavin.reid@ed.ac.uk | E-mail: Jo.Williams@ed.ac.uk |

**Thank you for your help**.

Sincerely yours,

**Elpida Pavlidou**

---------------------------------------------------------------------------------------------

I give permission for my son/daughter______________________________ to participate in this study.

(son/ daughter's name)

# APPENDIX E

# EXAMPLE OF PARENTAL THANKING LETTER

Dear Parent,

I am Elpida Pavlidou a second year PhD student at the University of Edinburgh, Moray House School of Education and I am conducting a study that aims to explore aspects of implicit learning (learning without awareness) in children between the ages of 9-12.

I am about to start working with your child in an individual basis and for one session only, which will last about 25-30 minutes the most. The session will be held probably within next week. The task is computer-based and is constructed by published work. All the information regarding your child will be **strictly confidential**.

I would like to thank you for giving permission for your child to take part in my study and I hope that the results of my attempt will be greatly beneficial towards a more fruitful educational environment.

Sincerely yours,

Elpida Pavlidou

## APPENDIX F

## STUDY 1 MATERIALS

### F.1. Original (Knowlton & Squire, 1996) stimulus set

| Training items | Testing items |
|---|---|
| XXVT | VJTV |
| VXJJJJ | XXVXJ |
| XXVJ | XVTV |
| VJTVXJ | JXVT |
| XXVXJJ | VJJXVT |
| XVT | VXJ |
| VJTVX | XXVTV |
| XXXVX | VXJTJ |
| VXJJ | XVJTVX |
| XXXVT | VXJJX |
| XXXVTV | XXVTVJ |
| VJTXVJ | XXTX |
| XVJTVJ | TVJ |
| VJ | VXVJ |
| VJTVX | XXVVJJ |
| XVXJ | VJTXVX |
| XXVXJ | VX |
| XVXJJJ | VJTVT |
| XVXJJ | XJJ |
| XXXXVX | VTVJJ |
| XVX | XVXT |
| VJTVTV | XXVJJJ |
| VT | VTVJ |
| | XVJTVT |
| | XXJJ |
| | VTV |
| | XXV |
| | XVTVJ |
| | XVTVJJ |
| | VTVJJ |
| | XVXV |
| | XVXVJ |

### F. 2. Developed stimulus set

Training items

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Testing items

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F.3. Chunk strength of developed task items

| Items | G *hcs* | G *lsc* | NG *hcs* | NG *lcs* |
|---|---|---|---|---|
| | 31.2 | 17.7 | 20.4 | 15 |
| | 20.4 | 15.6 | 24.6 | 14.4 |
| | 29.1 | 15.6 | 21 | 15 |
| | 23.7 | 19.8 | 21.6 | 18 |
| | 22.8 | 15 | 20.4 | 8.4 |
| | 21.9 | 19.2 | 36 | 18 |
| | 20.4 | 17.7 | 29.4 | 18 |
| | 39 | 14.9 | 27.3 | 20.1 |
| **Mean** | ***26.1*** | ***16.7*** | ***25.1*** | ***15.7*** |

## F.4. Instructions

(a) *Implicit instructions:* Welcome! This study has two parts. During the first part, you will see a series of items that are made up of geometric shapes. You just have to observe them very carefully. If you have any question, ask the experimenter now. You should not ask any questions while observing the geometric shapes.

(b) *Explicit instructions:* Welcome! This study has two parts. During the first part, you will see a series of items that are made up of geometric shapes. The order of the geometric shapes within each of these items is determined by a rather complex set of rules. These rules allow only certain figures to enclose/follow other figures in each item. So, you have to try and memorize a big number of items made up of geometric shapes. In order to accomplish this, it will be very useful to try and figure out these rules (i.e., which shapes can follow other shapes and which cannot). This will certainly help you learn and memorize the items composed of geometric shapes. If you have any question, ask the experimenter now. You should not ask any questions while observing the geometric shapes.

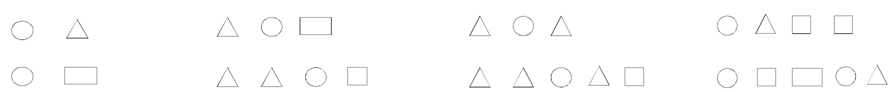
# APPENDIX G

# STUDY 2 MATERIALS

## G.1. Developed stimulus set

*(a) Training stimuli*

**Card 1** **Card 2** **Card 3** **Card 4**



*(b) Testing stimuli*

## G. 2. Chunk strength of testing stimulus set

| Items | G *hcs* | G *lsc* | NG *hcs* | NG *lcs* |
|---|---|---|---|---|
| | 1.6 | 1 | 1.42 | 1.14 |
| | 1.3 | 1 | 2.4 | 1.2 |
| | 2.3 | 0.8 | 2.2 | 1.2 |
| | 1.42 | 0.85 | 2.6 | 0.4 |
| | 2.42 | 1 | 1.28 | 0.3 |
| **Mean** | ***1.8*** | ***0.93*** | ***1.46*** | ***0.84*** |

## G.3. Instructions

(a) *Before training:* “I will show cards that have sequences of geometrical shapes printed on them. Try to pay your utmost attention and memorize the sequences. I will show each card for 15 seconds and once I put it down, use the printed shapes to make the sequences exactly as you saw them on the card. If you do not get it right with the first trial we will do it again until you get it right.”

(b) *After training:* “Although you did not know it, the sequences you have just memorized were following some rules. I will show you now on the computer new sequences of the same geometrical shapes and you need to decide if the new sequences follow the same rules as the sequences you have just memorized or not. If you think they follow the same rules say YES and if you think they don’t follow the same rules say NO. Because you do not know what the rules are, you can try to figure them out. However, if you are not sure you can guess. The sequences will remain on screen until you give a YES or NO answer but try to respond as quickly as possible”.

# APPENDIX H

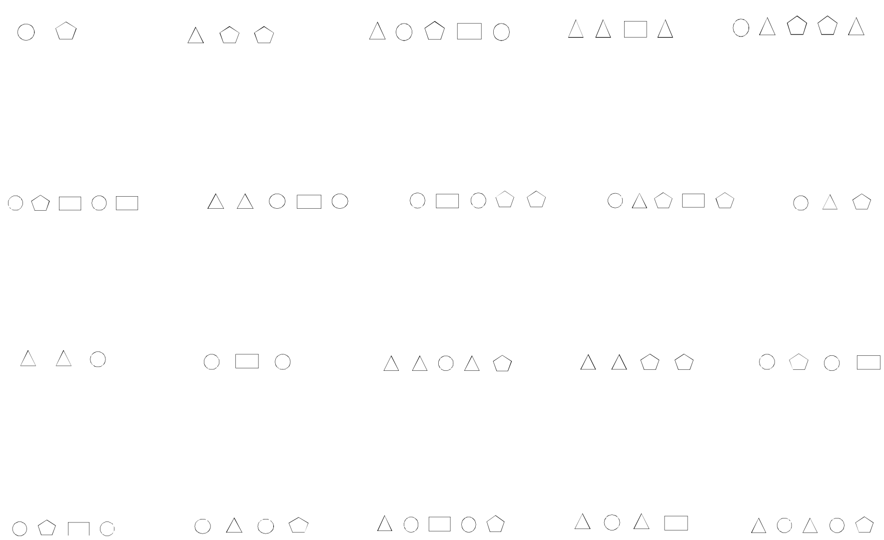
# STYDY 3 MATERIALS

## H.1. Transfer task developed items

*(a) Training stimuli*

**Card 1** **Card 2** **Card 3** **Card 4**

*(b) Testing stimuli*



## H.2. Chunk strength of transfer stimulus set

| Items | G *hcs** | G *lsc*** | NG *hcs** | NG *lcs*** |
|---|---|---|---|---|
| | 1.4 | 1.2 | 2.2 | 1.1 |
| | 1.8 | 1 | 1.5 | 1.2 |
| | 2.5 | 0.9 | 2.6 | 0.9 |
| | 1.5 | 0.8 | 2.1 | 0.3 |
| | 2.3 | 1.1 | 1.2 | 0.2 |
| **Mean** | ***1.9*** | ***1*** | ***1.84*** | ***0.74*** |

## H.3. Instructions (Transfer task)

(a) *Before training:* "I will show cards that have sequences of geometrical shapes printed on them. Try to pay your utmost attention and memorize the sequences. I will show each card for 15 seconds and once I put it down, use the printed shapes to make the sequences exactly as you saw them on the card. If you do not get it right with the first trial we will do it again until you get it right."

(b) *After training:* "Although you did not know it, the sequences you have just memorized were following some rules. I will show you now on the computer new sequences of different geometrical shapes and you need to decide if the new sequences follow the same rules as the sequences you have just memorized. If you think they follow the same rules say YES and if you think they don't follow the same rules say NO. If you are not sure what the rules are, you can guess. The sequences will remain on screen until you give a YES or NO answer but try to respond as quickly as possible".

# APPENDIX I

# PUBLICATIONS

**PAPER 1:**

Pavlidou, E., Williams, J. & Kelly, M.L. (2009). Artificial Grammar Learning in children with and without developmental dyslexia. *Annals of Dyslexia*, *59*, 55-77. Reproduced with permission from the Annals of Dyslexia, © The International Dyslexia Association.

**PAPER 2:**

Pavlidou, E., Kelly, M.L. & Williams, J. (2010). Do children with developmental dyslexia have impairments in implicit learning? *Dyslexia,16(2), 143-161.* Reproduced with permission from Dyslexia, © 2010 John Wiley & Sons, Ltd.